

**ECOHYDROLOGICAL PLANNING FOR THE WOODLANDS:
LESSONS LEARNED AFTER 35 YEARS**

A Dissertation

by

BO YANG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2009

Major Subject: Urban and Regional Sciences

**ECOHYDROLOGICAL PLANNING FOR THE WOODLANDS:
LESSONS LEARNED AFTER 35 YEARS**

A Dissertation

by

BO YANG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Approved by:

Co-Chairs of Committee,	Chang-Shan Huang
	Ming-Han Li
Committee Members,	George O. Rogers
	Jon E. Rodiek
	X. Ben Wu
Head of Department,	Forster Ndubisi

August 2009

Major Subject: Urban and Regional Sciences

ABSTRACT

Ecohydrological Planning for The Woodlands: Lessons Learned After 35 Years.

(August 2009)

Bo Yang, B.Arch., Huazhong University of Science & Technology;

M. Arch., Huazhong University of Science & Technology

Co-Chairs of Advisory Committee: Dr. Chang-Shan Huang
Dr. Ming-Han Li

The Woodlands, Texas, is a 27,000-acre new town created with Ian McHarg's ecohydrological planning approach. The Woodlands is the best example of ecologically based new town planning in the United States during the 1970s. The Woodlands survived storms in excess of one-hundred-year levels in 1979 and 1994 with little property damage, while Houston, 31 miles away, was severely flooded in both events. For the past three decades, very few studies have been conducted to assess the effectiveness of McHarg's planning approach. The objective of this study is three fold: (1) To document McHarg's ecohydrological planning concepts, implementation and unveil the barriers to continue his approach; (2) To compare flood mitigation effectiveness of different drainage systems used in The Woodlands development; and (3) To simulate "what if" land-use scenarios using different planning approaches.

Original development information is collected from published monographs, journal articles, newspapers and designers' collections. Geographic Information System (GIS)

parcel data are obtained from Montgomery County Appraisal District. Streamflow data are acquired from the USGS website. Weather data are downloaded from the NOAA website. Land use and land cover data are collected from various national datasets. Two GIS hydrologic models—the Soil and Water Assessment Tool (SWAT) and the Kinematic Runoff and Erosion model (KINEROS)—are used for watershed simulation. The statistic analysis tool SPSS is used for correlation analysis.

Results show that McHarg's planning approach was followed in the early phases of development (1974-1996) but was largely abandoned in the later phases when its ownership was changed in 1997. McHarg's approach ceased to be implemented because of the low public acceptance of ecohydrological planning strategies and the conflicts between short-term investment return and long-term environmental stewardship. In addition, comparative study shows that the early phases of development responded to rainfall similarly to its pre-development forest conditions. However, the later phases generated runoff volumes three times greater than the early phases.

Therefore, McHarg's ecohydrological planning approach demonstrates flood mitigation effectiveness that is superior to the conventional approach. Finally, using soil permeability to coordinate development density and land use presents a viable solution for mitigating environmental impacts from a stormwater perspective.

DEDICATION

I dedicate this dissertation to my wife and my parents.

ACKNOWLEDGEMENTS

My deepest thanks go to my committee co-chairs, Dr. Chang-Shan Huang and Dr. Ming-Han Li. Their guidance, encouragement and support led me to the end of my doctoral journey and into the start of my academic career. More importantly, their insights and passion for design and research, in combination with their inspiration and spirit in scholarship will benefit my life-long academic pursuit.

I am also deeply grateful to my committee members, Dr. George Rogers, Dr. Jon Rodiek, and Dr. Ben Wu, for their guidance and support throughout the course of this research. Dr. Forster Ndubisi, the department head, has provided enormous help with my doctoral study and career development. My sincere gratitude also goes to him. I would also like to thank the faculty, the staff, and the graduate colleagues for their support and assistance. I also want to extend my gratitude to the Texas Water Resource Institute and the U.S. Geopolitical Survey for funding this research.

I also thank so many people who have helped me in this process. My sincere thanks go to Mr. Steven Johnson, Ms. Debra Staley, Mr. Mike Mooney, Ms. Kate Halton, Mr. Jeffery East, Dr. Jin Ki Kim, Dr. Raghavan Srinivasan, Dr. Xuesong Zhang, Ms. Susan Gilstrap, Mr. Casey Johnson, Mr. Aaron Wendt, Ms. Catherine Nash, Mr. William Bass and Mr. Shelby Fritsche.

Finally, thanks to my parents for their encouragement and to my wife, Shujuan Li, for her extraordinary patience and love.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
DEDICATION	v
ACKNOWLEDGEMENTS	vi
TABLE OF CONTENTS	vii
LIST OF FIGURES.....	x
LIST OF TABLES	xiv
 CHAPTER	
I INTRODUCTION	1
1.1 Background	1
1.2 Past Studies	12
1.3 Key Terminology of Title	13
1.4 Research Objectives	14
1.5 Research Questions and Hypotheses.....	15
1.6 Research Method.....	16
1.6.1 Simulation	18
1.6.2 Correlation Analysis.....	19
1.6.3 Archival Study.....	21
1.7 Significance.....	22
1.8 Dissertation Structure	23
 II ASSESSING PLANNING APPROACHES BY WATERSHED	
 STREAMFLOW MODELING: CASE STUDY OF THE WOODLANDS,	
TEXAS	25
2.1 Synopsis	25
2.2 Introduction	26
2.3 Materials and Methods	28

CHAPTER	Page
2.3.1 Study Site	28
2.3.2 Data	31
2.3.3 Measurement	31
2.4 Result.....	39
2.4.1 Land Use Change and Development Location.....	39
2.4.2 SWAT Simulation	42
2.4.3 KINEROS Simulation	47
2.5 Discussion	51
2.6 Conclusions	55
III DRAINAGE DESIGNS IN THE WOODLANDS, TEXAS: COMPARATIVE	
STUDY OF OPEN SURFACE AND CONVENTIONAL DRAINAGE	
SYSTEMS IN COMMUNITY DEVELOPMENT	57
3.1 Synopsis	57
3.2 Introduction	59
3.3 Study Site	61
3.4 Data	64
3.4.1 Impervious Area.....	64
3.4.2 Streamflow	64
3.4.3 Precipitation	65
3.5 Data Treatment.....	65
3.5.1 Streamflow	65
3.5.2 Excluding Lake/Reservoir Detention Effect	67
3.5.3 Precipitation-Streamflow Data Pair Selection.....	71
3.6 Analysis.....	73
3.6.1 Impervious Area.....	73
3.6.2 Watershed Runoff Volume.....	73
3.6.3 Streamflow Response.....	74
3.6.4 Precipitation-Streamflow Correlation	74
3.7 Results	76
3.7.1 Impervious Area.....	76
3.7.2 Watershed Runoff Volume.....	77
3.7.3 Streamflow Response.....	78
3.7.4 Precipitation-Streamflow Correlation Analysis	79
3.8 Discussion	96
3.9 Conclusions	99

CHAPTER	Page
IV MCHARG’S WOODLANDS AFTER 35 YEARS: WHAT WORKS AND	
WHAT DOES NOT	102
4.1 Synopsis	102
4.2 Introduction	103
4.3 Background and Past Studies	104
4.4 Project Precedents	106
4.5 Ecohydrological Plan	109
4.5.1 Preserve Permeable Soils	111
4.5.2 Preserve Forest Environment	118
4.5.3 Open Surface Drainage	121
4.6 Design Implementations.....	121
4.6.1 Preserve Permeable Soils	122
4.6.2 Preserve Forest Environment	123
4.6.3 Open Surface Drainage	125
4.7 Flooding: After Ecological Plans Were Abandoned	127
4.8 Barriers to Implement Ecohydrological Plans	128
4.8.1 Homeowner (Demand).....	128
4.8.2 Developer (Supplier).....	129
4.8.3 Designer (Professional Service).....	130
4.8.4 Government (Policy Maker).....	132
4.9 Discussion	134
4.10 Conclusions	137
V SUMMARY AND CONCLUSION.....	140
5.1 Review and Conclusions	140
5.2 Study Limitation.....	143
5.3 Future Research.....	144
REFERENCES.....	146
VITA	154

LIST OF FIGURES

	Page
Fig. 1-1. The Woodlands and the regional context..	3
Fig. 1-2. Drainage conditions in the early and later phases of The Woodlands.....	5
Fig. 1-3. Residential villages of The Woodlands, Texas..	7
Fig. 1-4. Development year of The Woodlands villages.....	11
Fig. 1-5. Study flow diagram.	17
Fig. 2-1. Panther Creek watershed development and stream network..	30
Fig. 2-2. Land-use scenarios 1-5 and watershed soil conditions A-D.....	34
Fig. 2-3. Land-use and land-cover distribution in the Panther Creek watershed (The Woodlands).	39
Fig. 2-4. Soil distribution in the Panther Creek watershed (The Woodlands) and three development phases.....	41
Fig. 2-5. Simulated and observed surface runoff for the calibration and validation periods at USGS gauge station #08068450.....	44
Fig. 2-6. Simulated annual surface runoff of five land-use scenarios.....	46
Fig. 2-7. Simulated watershed peak discharges of four land-use scenarios during three rainfall frequencies.....	48
Fig. 2-8. Spatial distribution of peak discharge during 100-yr storms.....	50
Fig. 3-1. Different drainage systems in The Woodlands.....	61
Fig. 3-2. Panther Creek watershed development and two sub-watersheds.	63
Fig. 3-3. Cumulated percentage of developed area in Watershed #1 (open drainage) and Watershed #2 (conventional drainage).....	76

	Page
Fig. 3-4. Surface runoff depths of Watershed #1 (open drainage) and Watershed #2 (conventional drainage).....	78
Fig. 3-5. Annual precipitation (m) and streamflow response value ($\text{m}^3\text{s}^{-1}\text{m}^{-1}$) of Watershed #1 (open drainage) and Watershed #2 (conventional drainage).....	79
Fig. 3-6. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of water years 1975-1976.....	81
Fig. 3-7. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of water years 2000-2002.....	82
Fig. 3-8. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of water year 2000, before excluding the lake detention effect. ...	84
Fig. 3-9. R^2 correlation coefficients of precipitation (>6 mm) and daily mean streamflow of water year 2000, before excluding the lake detention effect. ...	84
Fig. 3-10. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of water year 2001, before excluding the lake detention effect. .	85
Fig. 3-11. R^2 correlation coefficients of precipitation (>6 mm) and daily mean streamflow of water year 2001, before excluding the lake detention effect. .	85
Fig. 3-12. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of water year 2002, before excluding the lake detention effect. .	86
Fig. 3-13. R^2 correlation coefficients of precipitation (>6 mm) and daily mean streamflow of water year 2002, before excluding the lake detention effect. .	86
Fig. 3-14. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of water years 2000-2002, after excluding the lake detention effect.....	89
Fig. 3-15. R^2 correlation coefficients of precipitation (>6 mm) and daily mean streamflow of water years 2000-2002, after excluding the lake detention effect.....	89
Fig. 3-16. R^2 correlation coefficients of precipitation (>0 mm) and daily peak streamflow of water years 2000-2002, after excluding the lake detention effect.....	90

	Page
Fig. 3-17. R ² correlation coefficients of precipitation (>6 mm) and daily peak streamflow of water years 2000-2002, after excluding the lake detention effect.....	90
Fig. 3-18. R ² correlation coefficients of precipitation (>0 mm) and yesterday's mean streamflow of water years 2000-2002, after excluding the lake detention effect.....	91
Fig. 3-19. R ² correlation coefficients of precipitation (>6 mm) and yesterday's mean streamflow of water years 2000-2002, after excluding the lake detention effect.....	91
Fig. 3-20. R ² correlation coefficients of precipitation (>0 mm) and yesterday's peak streamflow of water years 2000-2002, after excluding the lake detention effect.....	92
Fig. 3-21. R ² correlation coefficients of precipitation (>6 mm) and yesterday's peak streamflow of water years 2000-2002, after excluding the lake detention effect.....	92
Fig. 3-22. R ² correlation coefficients of precipitation (>0 mm) and daily mean streamflow during 2000-2002, before excluding the lake detention effect....	94
Fig. 3- 23. R ² correlation coefficients of precipitation (>0 mm) and daily mean streamflow during 2000-2002, after excluding the lake detention effect.	94
Fig. 3-24. R ² correlation coefficients of precipitation (>0 mm) and yesterday's mean streamflow during 2000-2002, after excluding the lake detention effect.	95
Fig. 3-25. R ² correlation coefficients of precipitation (>0 mm) and yesterday's peak streamflow during 2000-2002, after excluding the lake detention effect.	95
Fig. 4-1. The first mater plan of The Woodlands, by architect Karl Kamrath, 1966.....	107
Fig. 4-2. Design Synthesis. The dark areas are flood plains of the three major creeks. Map shows primary open space and recharge soils..	112
Fig. 4-3. Land-use Plan. The darker the area, the higher the building density is. High density land-uses were proposed relatively near the roads and to avoid prime recharge soils..	113

	Page
Fig. 4-4. Site-level design guidelines. Housing cluster and grouped parking conformed to the boundaries of soils with low infiltration capacities..	114
Fig. 4-5. Development guidelines for site with different soil conditions.....	116
Fig. 4-6. Watershed storage capacity of Phase I development.....	118
Fig. 4-7. Clearance percentage for vegetation types in Phase I development.....	120
Fig. 4-8. Different drainage solutions and landscapes in The Woodlands.....	128

LIST OF TABLES

	Page
Table 1-1 Population and land area of residential villages of The Woodlands.....	7
Table 1-2 Regional significant storms in The Woodlands and Houston region 1979-2008.....	9
Table 1-3 Research method.....	17
Table 1-4 Research method selection consideration.....	18
Table 1-5 Hydrologic models commonly used in the landscape architecture and planning field.....	18
Table 1-6 Regression models commonly used for precipitation-streamflow correlation analysis.....	20
Table 1-7 Interpretation of R^2 correlation coefficient.....	21
Table 2-1 Impervious cover ratio index.....	36
Table 2-2 Development location on different soil groups in the Panther Creek watershed (The Woodlands) during three development phases.....	40
Table 2-3 Land-use scenarios and observed land-use conditions in the Panther Creek watershed (The Woodlands).....	43
Table 2-4 Model efficiency and statistics from Ordinary Least Square regression analyses for the calibration and validation periods.....	44
Table 2-5 Simulated watershed outputs, average of year 2001-2005.....	47
Table 3-1 Variables in Equation 2 to calculate precipitation depths needed to fill the lake and the reservoir from the normal water level elevations to the maximum water level elevations in water years 2000-2002.....	69
Table 3-2 Two different methods to calculate precipitation depths needed to exclude the lake/reservoir detention effect.....	71

	Page
Table 3-3 R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of Watershed #1 (open drainage) and Watershed #2 (conventional drainage).....	80
Table 3-4 Before excluding lake/reservoir detention effect, R^2 correlation coefficients of precipitation and daily mean streamflow of Watershed #1 (open drainage) and Watershed #2 (conventional drainage).....	83
Table 3-5 After excluding the lake/reservoir detention effect, R^2 model coefficients of the daily model and the simplified lagged model for Watershed #1 and Watershed #2.....	88
Table 4-1 Site planning guidelines for soils.....	115
Table 4-2 Land-use change in The Woodlands from 1996 to 2001.....	125

CHAPTER I

INTRODUCTION

1.1 Background

Since the World War II, the United States has been experiencing massive suburban sprawl (Ewing 1997; Burchell et al., 2002). The sprawl developments were criticized, especially in the context of the environmental crisis during the 1960s and 1970s, for the “ecological damage, excessive energy use, high infrastructure cost, and loss of open space” (Forsyth, 2002, p. 387). A series of national policies including the 1969 National Environmental Policy Act (NEPA), the 1972 Clean Water Act and the 1973 Endangered Species Act were enacted to curb the environmental degradation.

In 1970, the Urban and New Community Development Act was passed, under which the Department of Housing and Urban Development (HUD) can provide a maximum loan at \$50 million for new town developers (Malone, 1985; Morgan and King, 1987). Social and environmental issues became focuses of the HUD Title VII new town projects due to the influence of NEPA. Within this context, The Woodlands, Texas, was created during the American’s climax of new town development in an attempt to find an alternative to suburban sprawl (McHarg and Steiner, 1998).

This dissertation follows the style and the format of *Landscape and Urban Planning*.

George Mitchell, a self-made oil and real estate business man, launched The Woodlands project in a pine forest 48 kilometers north of Houston. His personal interests in environmental stewardship and social equity motivated him, rather than for pure profit (Morgan and King, 1987). Among the 13 HUD Title VII new town projects, The Woodlands was the only one which did not fail to meet the financial obligations under the HUD loan guarantees (Morgan and King, 1987).

Mitchell's most important step in developing The Woodlands was to hire Ian McHarg—ecologist, landscape architect and urban planner (Galatas and Barlow, 2004). McHarg was known as a pioneer of ecological planning and design and had helped to create NEPA's intellectual foundation and methodological framework (McHarg and Steiner, 1998). In his influential book *Design with Nature*, McHarg stated his design philosophy that design should keep nature in mind (McHarg, 1969). McHarg's ecological planning concepts were well demonstrated in The Woodlands development. The Woodlands is also regarded as “the best example of ecologically based new town planning in the United States during the 1970s” (McHarg, 1996, p.325).

Started in a lush loblolly pine forest north of Houston (Fig.1-1), The Woodlands site presented a number of constraints for the development. The site was extremely flat with limited permeable soils to allow proper drainage. 48 kilometers to the south, Houston metropolitan area was beleaguered by flooding. Conventional drainage solution usually failed. If The Woodlands were to be developed following the conventional approach, the water table will decrease and the natural hydrologic balance will be interrupted. Thus trees will die, downstream may get flooded, and high-rise buildings in downtown Houston may sink (McHarg and Steiner, 1998).

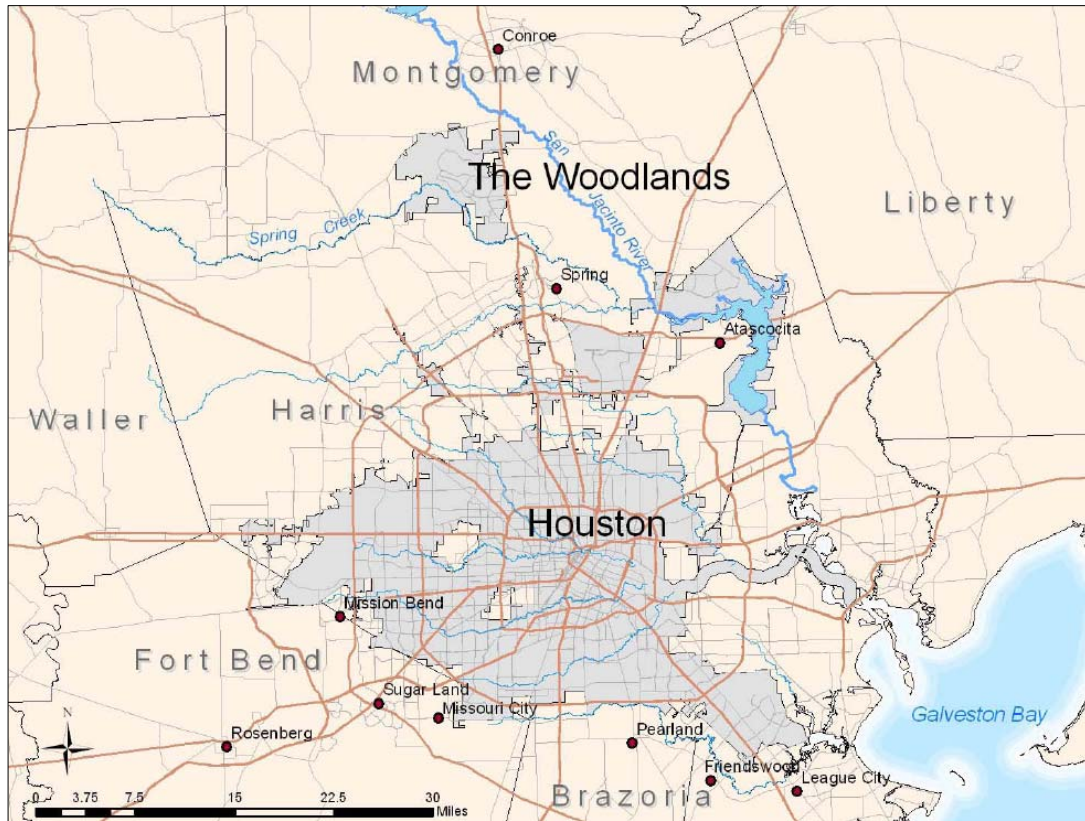


Fig.1-1. The Woodlands and the regional context. Source: Haunt, 2006, p.7.

The development goals which McHarg established were to preserve the pine forest after development and to minimize the development impacts on the natural landscape (WMRT, 1973b). To meet these goals, McHarg put emphasis on maintaining the natural hydrologic balance of the site (WMRT, 1973b). A series of strategies were developed to reduce excessive runoff and to maintain the site hydrologic cycle. These strategies included protecting high permeable soils for runoff recharging, maintaining forest preserve, and using open surface drainage (WMRT, 1973c; 1974).

McHarg's concepts were strictly followed in the first village (Village of Grogan's Mill) and part of the second village (Village of Panther Creek), but were adjusted to meet the homeowners' preferences in the later rest villages (Kutchin, 1998; Galatas and Barlow, 2004) (Fig. 1-2). A significant setback from the original plans occurred in 1985, although the spirit of the "ecological plan" remained in the community mission statement (Girling and Helphand, 1994). The year 1997 witnessed a further adjustment to the plans when George Mitchell sold The Woodlands ownership to Crescent Real Estate Equities and Morgan Stanley Real Estate Fund II, after which development sped up (Clay, 1998; Galatas and Barlow, 2004).



Fig. 1-2 (a)



Fig. 1-2 (b)



Fig. 1-2 (c)



Fig. 1-2 (d)



Fig. 1-2 (e)



Fig. 1-2 (f)

Fig. 1-2. Drainage conditions in the early and later phases of The Woodlands. McHarg's concepts were followed before 1997. After the ownership was changed 1997, McHarg's concepts were largely abandoned.

- (a). Drainage in neighborhoods before 1997: open surface drainage swale
- (b). Drainage in neighborhoods after 1997: curb-and-gutter drainage with fewer trees
- (c). Creek conditions before 1997: natural vegetation well preserved
- (d). Creek conditions after 1997: concrete drainage channel and mowed stream bank
- (e). Pond conditions before 1997: natural bank with well-kept vegetation
- (f). Pond conditions after 1997: manicured lawn with fewer trees

The Woodlands is currently 27,000-acre in size. There are eight residential villages in The Woodlands. Seven of them are located in Montgomery County and the eighth village is located in Harris County (Fig.1-3, Table 1-1). The Woodlands 2006 population exceeded 83,000 (The Woodlands Development Company, 2007). It is expected that The Woodlands will be substantially completed around 2015 (Galatas and Barlow, 2004).

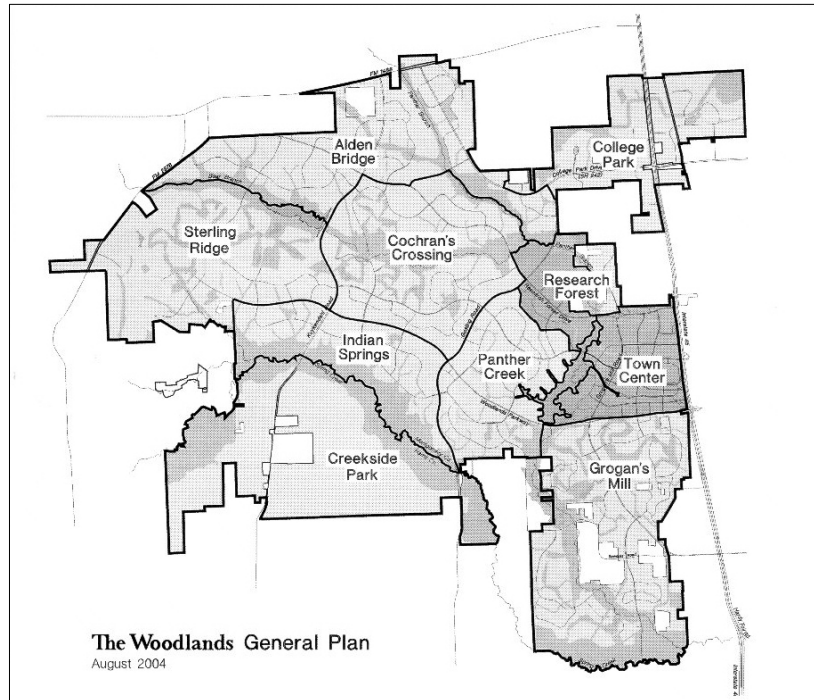


Fig.1-3. Residential villages of The Woodlands, Texas. Source: Galatas and Barlow, 2004, n.p.

Table 1-1

Population and land area of residential villages of The Woodlands

Village	Open Year	Area (acre)	Population (2006)	Pop. Density (cap./acre)
Grogan's Mill	1974	4,320	13,512	3.1
Panther Creek	1979	2,070	13,957	6.7
Cochran's Crossing	1983	3,358	16,098	4.8
Indian Springs	1984	1,879	6,401	3.4
Alden Bridge	1994	3,602	20,936	5.8
College Park	2000	1,073	4,428	4.1
Sterling Ridge	2001	4,061	7,543	1.9
Creekside Park	2007	3,492	7,100 (planned)	N/A

Source: The Woodlands Demographics. The Woodlands Development Company, 2007.

McHarg's planning approach was regarded to protect the community from flooding in a number of historical storms. The Woodlands survived significant storms in 1979, 1987 and 1994 when neighborhoods nearby got severely flooded (NOAA, 1987; Girling and Kellett, 2005). However, McHarg's ecohydrological planning approach was largely shifted to the conventional development approach after the third village. Development sped up especially after its ownership was changed in 1997 (Galatas and Barlow, 2004).

The encroached green infrastructure failed to protect The Woodlands in a 2000 storm and the 2008 Hurricane Ike (NOAA, 2000; Madere, 2008). In 2000, NOAA reported flooding in The Woodlands after a modest 2-inch storm. Again in the 2008 Hurricane Ike, a large territory of The Woodlands was flooded. Neither the 2000 nor the 2008 storm was greater than the 1979's or the 1994's. Also, the natural conditions (e.g., vegetation, topography elevation, etc.) are close across The Woodlands (Table 1-2). In Hurricane Ike, western Woodlands, containing villages developed after 1997, was particularly hard-hit (Fig.1-4). However, early villages developed following McHarg's approach remained safe places (Madere, 2008).

Table 1-2

Regional significant storms in The Woodlands and Houston region 1979-2008

Before 1997—McHarg’s approach was followed			
Date	Intensity	Flooded Area & Info	Source
7/24-25/1979	43” in	• Houston	NOAA;
Storm Claudette	24 hrs	(30 miles south of Woodlands)	Girling and Kellett, 2005
9/28/1987	5”	• Oak Ridge North East to Woodlands	NOAA
		• Timber Ridge Southwest to Woodlands	
10/16-18/1994	4 - 29”	• Houston	NOAA;
Hurricane Rosa	in 36 hrs	(30 miles south of Woodlands)	Roger and Barlow, 2004
After 1997— McHarg’s approach was abandoned			
Date	Intensity	Flooded Area & Info	Source
4/2/2000	2” in 6 hrs	• Woodlands Road impassible, no further details on flooded area	NOAA
		• State Highway 105	
		• River Plantation Northeast to Woodlands	
9/13/2008	4” in 6 hrs	• West part of Woodlands (particularly in villages developed after 1997)	Madere, 2008 (Houston Chronicle)

Note: Hurricane Allison (6/9/2001) caused severe flooding in Houston. NOAA reported flooding in Montgomery County (where The Woodlands is located), but no further information is available on specific flooded areas in the County.

Houston Chronicle reported substantial structure and tree damage after Hurricane Ike. An initially drive-by assessment of properties by The Woodlands Fire Department showed 400 to 450 homes suffering substantial damage (Madere, 2008).

Additionally, flooding was observed in neighborhoods and parks, especially those developed after 1997. 17 parks were closed because of the hurricane damage, 15 of which were located in villages built by the new developers. Some streets and thoroughfares got flooded and impassable, including parts of Lake Woodlands Drive and Research Forest Drive in north Woodlands. Grogan's Point, an infill development after 1997 but was in the first village, was also flooded (Madere, 2008). When open drainage was changed to curb-and-gutter drainage, residents began to complain about the flooded streets in heavy rainfall. However, residents in Grogan's Mill and Panther Creek villages seldom have such complaints (Galatas and Barlow, 2004; Haunt, 2006).

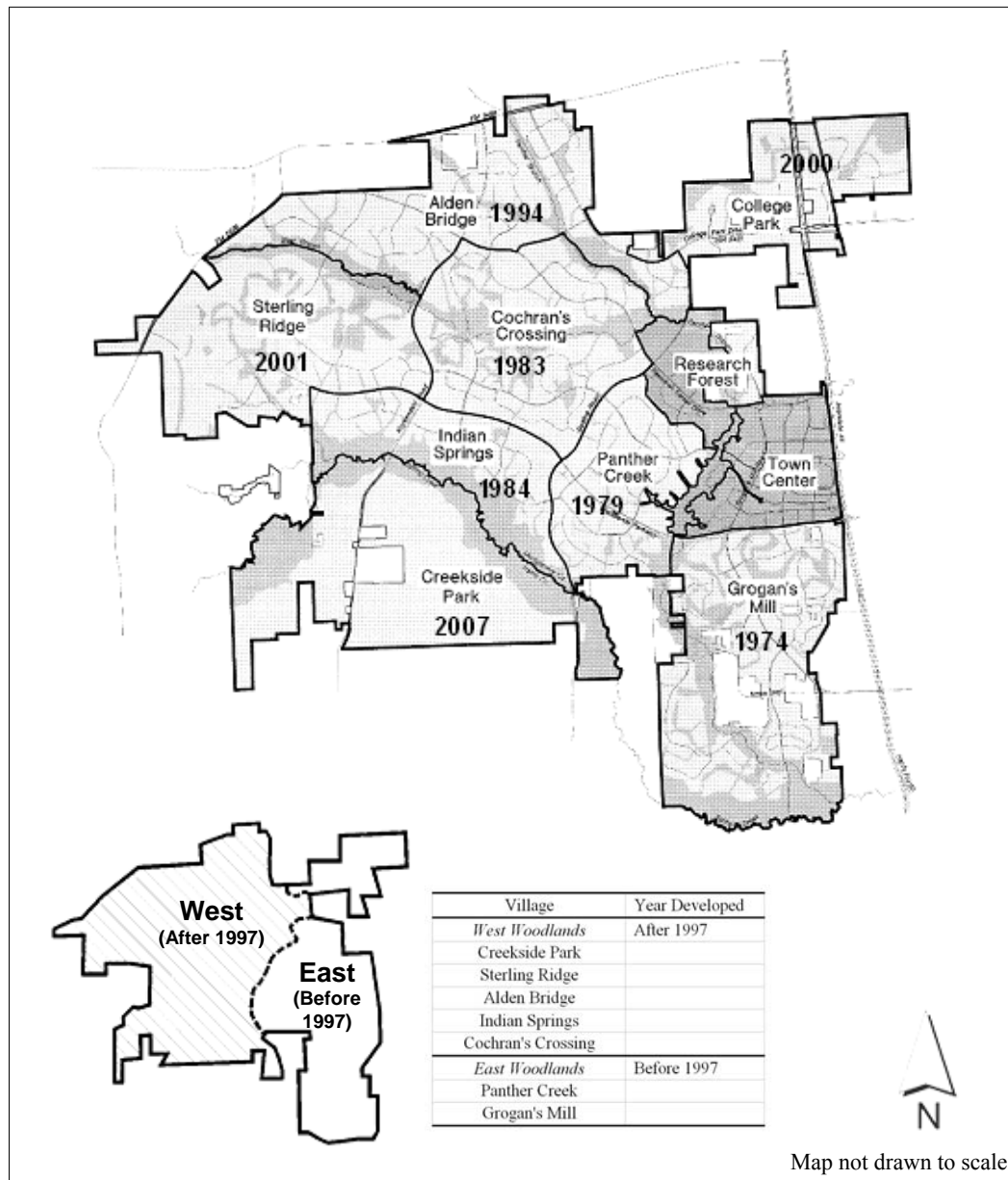


Fig.1-4. Development year of The Woodlands villages. Western Woodlands was particularly impacted by the 2008 Hurricane Ike. Base map adapted from Galatas and Barlow 2004, n.p.

1.2 Past Studies

An early article entitled “Ecological plumbing for the Texas coastal plain: The Woodlands new town experience” was written by McHarg and Sutton (1975) in the *Landscape Architecture Magazine*. The article features The Woodlands ecohydrological planning concepts. At the end of the article, McHarg called for Post Occupancy Evaluation. After 35 years, a number of studies were conducted on The Woodlands, including five books, one doctoral dissertation, and several journal articles. The first monograph, written by Morgan and King (1987), documents the early history of the development (1964-1983). The second monograph is written by Galatas and Barlow (2004), further adding the following 10 years. Ann Forsyth (2002, 2005) compares The Woodlands with two large-scale master planned communities: Irvine, California and Columbia, Maryland. Forsyth concludes that some social and environmental innovations from these projects would still benefit the current practice. Kim’s (2005) doctoral dissertation compares The Woodlands with north Houston development. The study concludes that stringent development guidelines lead to more ecologically structured environment than communities which are planned according to the conventional ordinances.

Most of these studies have mentioned McHarg’s ecohydrological planning approach, but majority of them are presented in a descriptive manner. In addition, very few have quantitatively assessed the stormwater management aspect, which was the key focus of McHarg’s plans. Finally, a boarder question interests planners and designers would be why The Woodlands was not replicated.

As McHarg suggested in the 1975 article that revisiting The Woodlands project will increase the collective knowledge of the profession (McHarg and Sutton, 1975). Documenting The Woodlands project evolution holds significant implications and will shed light for today's community planning and design practices. This study reviews the original planning concepts, how they were implemented, how they were changed, and what lessons we can learn. Using empirical data, this study quantitatively measures the effectiveness of McHarg's ecohydrological planning approach demonstrated in such a macro scale. This study also provides insights into how to promote ecological planning approach in the current planning and design practices.

1.3 Key Terminology of Title

McHarg coined the term "ecological plumbing" to represent the ecological drainage solution proposed in The Woodlands (McHarg and Sutton, 1975). The Woodlands is a multidisciplinary project which encompassed planning, ecology, hydrology, meteorology, limnology, and plant ecology, etc. At the end of the site ecological inventory, McHarg concludes that water is the agent which integrates the ecological and hydrological processes (WMRT, 1973a).

Circa 2000, a new discipline—ecohydrology—emerged which includes sciences of hydrology, ecology and hydrologic engineering. Ecohydrology is an interdisciplinary area studying hydrology and the ecological processes embedded in the hydrological cycle (Kundzewicz, 2000; Hannah et al., 2004). If using the contemporary terminology,

ecohydrologic planning perhaps best represents McHarg's "ecological plumbing" used in the 1970s. In this dissertation, *ecohydrological planning* is used as a substitute for "ecological plumbing" in order to better reflect the current literature.

1.4 Research Objectives

There are three fold objectives, focusing on McHarg's ecohydrological planning approach, stormwater management in specific.

The first objective is to determine which planning approach (conventional low-density, cluster high-density, or The Woodlands approach) causes less stormwater runoff.

The second objective is to examine which drainage solution is more effective in mitigating flood—McHarg's open surface drainage or the conventional underground pipe drainage.

The third objective is to document McHarg's ecohydrologic planning concepts, implementations, and unveil the barriers to continue this approach.

Hence this dissertation will answer the question that whether or not the ecohydrological planning approach mitigates environmental impacts from a stormwater management perspective.

1.5 Research Questions and Hypotheses

The central research question is “Did the ecohydrological planning work?” Specifically, four sub research questions are tackled. The questions and related hypotheses are presented below.

Research Questions

(1) Research question 1: Did The Woodlands development adhere to McHarg’s original plans overtime? In other words, did The Woodlands preserve more permeable soils than less permeable soils?

(2) Research question 2: Which community planning approach causes less development impacts in terms of stormwater runoff?

Five scenarios are developed and detailed procedures of scenario development are described in Chapter II.

(3) Research question 3: Which drainage solution is more effective in mitigating flood, McHarg’s open surface drainage or the conventional pipe drainage?

(4) Research question 4: Why McHarg’s ecohydrological planning approach was not implemented after the ownership change?

A boarder question is: Why The Woodlands was not replicated?

Central Hypothesis

Eco-hydrological planning approach used in The Woodlands is effective in mitigating environmental impacts from a stormwater management perspective.

Specific Hypotheses:

Hypothesis 1: The Woodlands preserve more permeable soils than less permeable soils in the community development.

Hypothesis 2: McHarg's planning approach causes less stormwater runoff compared with other planning approaches.

Hypothesis 3: Open surface drainage is more effective than conventional pipe drainage in mitigating flood.

Hypothesis 4: Under the new ownership, the market-driven type of development caused barriers to implement McHarg's ecohydrological planning approach.

1.6 Research Method

The study employs the case study strategy and uses three complementary methods: simulation, correlation analysis and archival study (Table 1-3, Fig. 1-5). Each method tests one or two of the above hypotheses based on the central research question. Since each method has its limitations, this study employs them simultaneously instead of using a single method. There are six major considerations of choosing the methods. None of the considerations is consistently ranked *low* among the three methods (Table 1-4). Hence these methods support one another and strengthen the research design.

Table 1-3

Research method

Method	Explanation	Past Study
Simulation	To simulate watershed outflows in different land-use scenarios, using hydrologic models	Arnold et al., 1994
Correlation analysis	To examine watershed responses to rainfall, using statistical analysis tool	Ferguson and Suckling, 1990 Rogers and DeFee, 2005
Archival study	To review development concepts, implementations, using published literature	Yin, 1994

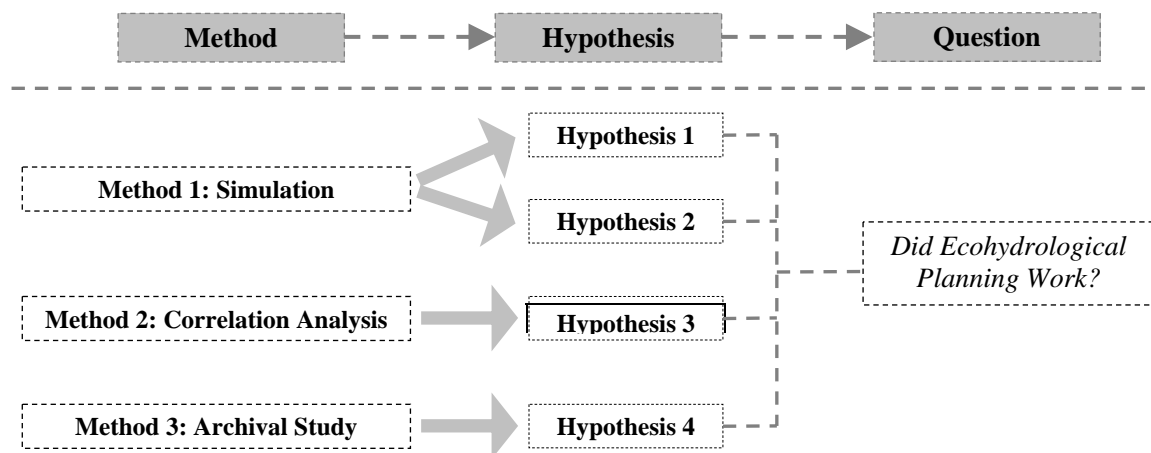


Fig.1-5. Study flow diagram.

Table 1-4

Research method selection consideration

Consideration	Simulation	Regression	Archival Study
Generalizability	Medium	Medium	Low
Required input-data precision	Medium	High	Low
Required sample size	High	High	Low
Level of in-depth understanding	Medium	Medium	High
Time efficiency	Medium	High	Low
Cost efficiency	High	High	Low

Note: Table adapted from Yin, 1994; Francis, 2001; 2002; Shadish et al., 2002.

1.6.1 Simulation

There are various hydrologic models used by landscape architecture and planning professionals (Table 1-5). These models could be grouped into two families: (1) continuous models, used for long-term watershed simulation and (2) event-based models, used for single-event peak discharges (Hann et al., 1994).

Table 1-5

Hydrologic models commonly used in the landscape architecture and planning field

Model Type	Example	Past Study
Continuous Models (long-term simulation)	HSPF	Bicknell et al., 1996
	SWAT	Arnold et al., 1994
	BASINS	EPA, 2001
Event Models (single-event peak discharge)	TR55	USDA, 1986
	KINEROS	Smith et al., 1995
	SWMM	Huber et al., 1981
	HEC-1	U.S. Army Corps of Engineers, 1985

The Soil and Water Assessment Tool (SWAT) model and the Kinematic Runoff and Erosion model (KINEROS) model were used in this study. The SWAT model was developed primarily for agricultural research purposes (Arnold et al., 1994; Arnold and Fohrer, 2005). An increasing number of studies have demonstrated its capability for urban watershed modeling (Allen et al., 2002; Lemonds and McCray, 2007). An important concept in the SWAT model is Hydrologic Response Unit (HRU). That is, for each unique combination of land-use and soil type, the model specifies a unique HRU. In The Woodlands planning, the most important planning strategy was to allocate different land uses onto different soil types. The SWAT model was chosen primarily because the HRU concept is the same as The Woodlands' planning concept.

The KINEROS model was chosen because it could simulate the spatial patterns of peak discharges in sub-watersheds. The spatial presentation component is not available in most of the rest models listed in Table 1-5. Another important reason to choose the SWAT and the KINEROS models was because both models were integrated into the ArcGIS interface. GIS is the major tool used in the study.

1.6.2 Correlation Analysis

There are three regression models commonly used for correlation analysis in the past studies, including linear, curvilinear and lagged models (Table 1-6). Based on the lagged model, a simplified lagged model was also developed. In this study, the linear model and the simplified lagged model are used. Both models use precipitation to

predict watershed outflow. The R^2 correlation coefficient indicate the sensitivity a watershed responses to rainfall. The R^2 values represent to what extent the drainage system is efficient in draining stormwater runoff (Ferguson and Suckling, 1990).

Table 1-7 presents the interpretations of R^2 values in different models. In the linear model, today's precipitation is used to predict today's watershed outflow. Thus, a high R^2 value suggests a condition vulnerable to flooding since daily precipitation and streamflow has a high correlation (Ferguson and Suckling, 1990). However, the situation is reversed in the simplified lagged model, in which yesterday's precipitation is used to predict today's watershed outflow. Therefore, a high R^2 value suggests a high correlation of yesterday's precipitation and today's streamflow. This means the drainage system is effective in detaining runoff. Runoff is captured and released slowly.

Table 1-6

Regression models commonly used for precipitation-streamflow correlation analysis

Model Type	Variable	Past Study
Linear model $Y = a + bX$	X: Precipitation Y: Outflow	Ferguson and Suckling, 1990 Jennings and Jarnagin, 2002 Rogers and DeFee, 2005
Curvilinear model $Y = a + b_1X + b_2X_2$	X: Precipitation Y: Outflow	Rogers and DeFee, 2005
Lagged model $Y = a + b_1X_1 + b_2X_2 + b_3X_3$	X ₁ : Precipitation of today X ₂ : Precipitation of yesterday X ₃ : Precipitation of the day before yesterday Y: Outflow	Rogers and DeFee, 2005
Simplified lagged model $Y = a + bX'$	X': Precipitation of yesterday Y: Outflow	

Table 1-7

Interpretation of R^2 correlation coefficient

Model Type	High R^2	Low R^2
Linear model $Y = a + bX$	<ul style="list-style-type: none"> • Watershed is sensitive to rainfall • Efficient drainage system • Vulnerable to flooding & may cause downstream flooding 	<ul style="list-style-type: none"> • Watershed is not sensitive to rainfall (e.g., natural forest) • Less efficient drainage system • Not vulnerable to flooding
Simplified lagged model $Y = a + bX'$	<ul style="list-style-type: none"> • Watershed is not sensitive to rainfall (e.g., natural forest) • Less efficient drainage system • Not vulnerable to flooding 	<ul style="list-style-type: none"> • Watershed is sensitive to rainfall • Efficient drainage system • Vulnerable to flooding & may cause downstream flooding

1.6.3 Archival Study

Archival study, as part of the case study strategy, is used in various disciplines such as law, business, medicine, political science and planning (Yin, 1993, 1994; Stake, 1995). This study employs similar methods used by Francis (2002) in the study of Village Homes in Davis, California. Specifically, the following sub methods will be used:

- Archival research of key documents on The Woodlands
- Literature review on monographs and past studies
- Internet searches
- Site visit (observation)

Renowned as an ecologically based new town development, The Woodlands is yet less known as to what extent McHarg's planning approach is effectively implemented. Archival study provides an in-depth understanding of The Woodlands

development from its beginning in the 1960s to present. Archival study reviews the original planning concepts, implementations and barriers to continue McHarg's approach. Each side of development is reviewed including homeowner (demand), developer (supplier), designer (professional service), and government (policy maker). Finally, this study suggests potential solutions to overcome the barriers.

1.7 Significance

This study provides empirical evidence to examine McHarg's ecohydrological planning approach. This study may become the first study which quantitatively tests this planning approach 35 years after its inception. In addition, this study enhances the understanding of environmental impacts stemmed from different community planning approaches. Finally, this study holds implications for the landscape architecture and planning professionals as it suggests important planning and design considerations.

Significance of this work could be reflected at the conceptual, methodological, policy, and pedagogical levels:

- *At the theoretical/conceptual level*, this study contributes to McHarg's theory of *Design with Nature* and supports McHarg's ecohydrological planning concepts.

Therefore, McHarg's concepts can be used to guide the practice and operation of today's community development. The Woodlands example can be instructive in how to analyze sites, develop standards, communicate objectives, and connect runoff management to future land use and general environmental management.

- *At the methodological level*, this study presents perhaps the first quantitative assessment of McHarg's stormwater management strategies. This study unpacks the complex relationships between various stormwater management tools and quantifies their roles in maintaining the natural hydrologic process.

- *At the policy level*, this study may help EPA to target perhaps alternative environmental polices in sustainable community development, with a better understanding of the site hydrology, soil, vegetation, material and quality of life.

- *At the pedagogical level*, this study has the potential to strengthen the education of environmental consciousness, for the general public and the design professionals. McHarg's influential idea that the biological disciplines should constitute an indispensable basis for planning is far-reaching for the planning education.

1.8 Dissertation Structure

This dissertation comprises of five chapters. Chapter I introduces study background and method. Chapter II to Chapter IV each presents an individual study, while all of them focus on the theme of ecohydrological planning. Chapter IV is Conclusion and Summary.

Chapter II employs a modeling approach to simulate “what if” land use scenarios when The Woodlands were to be planned using other different planning approaches.

Chapter III evaluates flood mitigation effectiveness of two different drainage solutions used in different phases of development.

Chapter IV documents the original ecohydrological planning concepts, illustrates the design implementations and explains the reasons why McHarg's plans were not followed.

Chapter V reviews the study, summarizes the conclusions and provides future research orientations.

CHAPTER II

ASSESSING PLANNING APPROACHES BY WATERSHED

STREAMFLOW MODELING: CASE STUDY OF THE

WOODLANDS, TEXAS

2.1 Synopsis

The Woodlands, Texas, has been well known as a town created with Ian McHarg's ecological planning approach using soil permeability to coordinate development densities and land use. Very few studies, however, have quantitatively measured the effect of this planning approach on stormwater management. In this study, five hypothetical land-use scenarios were created. These scenarios were compared with The Woodlands' 2005 condition using the Automated Geospatial Watershed Assessment (AGWA) tool that simulates watershed long-term streamflow and peak discharges during single storms. The objectives are to (1) assess how closely The Woodlands' actual development follows Ian McHarg's approach and (2) quantify the potential impact of different planning approaches on stormwater using watershed simulation. Streamflow data from U.S. Geological Survey gauge stations were used for AGWA model calibration and validation. The result indicates that McHarg's approach was more closely followed before 1997. After The Woodlands' ownership was sold in 1997, the later developments did not follow McHarg's approach. The departure from McHarg's

approach after 1997 is also reflected in the streamflow simulation result. The 2005 observed streamflow volume is 53% higher than that of the simulated condition if McHarg's approach was kept. Overall, McHarg's approach using soil permeability to coordinate development densities and land use is effective in mitigating flood especially during intense storm events.

2.2 Introduction

Urbanization-induced hydrological alterations have been extensively discussed in the literature (Paul and Meyer, 2001). Urban development reduces infiltration capacity of the natural landscape, concentrates stormwater flows, and results in water quality and quantity problems in receiving water bodies (Leopold, 1971; Schueler, 1994). For the last two decades, imperviousness continues to be the most common measure to quantify the effect of urban development on the watershed (Schueler, 1994; Arnold and Gibbons, 1996). Furthermore, not only the quantity, but also the spatial configuration of imperviousness influences watershed outflows (Hammer, 1972; Corbett et al., 1997; Rogers and DeFee, 2005). Alberti and Marzluff (2004) and Alberti et al. (2007) suggest both urban form and land cover pattern (amount, distribution, and arrangement) can be viable measures for those alterations.

The major urban development project of the past century in the United States has been the development of suburban communities. Conventional community development practice imposes a homogenous hardscape pattern on the natural landscape, giving little

consideration to advantageous drainage opportunities. Traditional drainage designs aim to remove stormwater as quickly as possible, thus providing a flooding problem downstream (Ferguson, 1998; Tunney, 2001). The current mitigation practice of using various detention and retention basins to arrest excessive runoff after storms is hindered in dense urban settings (Ellis and Marsalek, 1996; Booth and Jackson, 1997). In addition, if the basin is located inappropriately, it exacerbates flooding (Ferguson, 1991; Perez-Pedini et al., 2005). A more comprehensive hydrologic mitigation approach, called “low impact development” (LID), was advocated by the U.S. Environmental Protection Agency (EPA, 2000). LID combines a number of techniques, including storing, infiltrating, evaporating and releasing runoff slowly, at a rate not exceeding that of the pre-development condition. Infiltration as an important function of the LID techniques is perhaps the most viable method to lower runoff volume (Ferguson, 1995; Ellis and Marsalek, 1996; Echols, 2008).

The Woodlands, Texas, is the first master-planned community that employed an ecological approach in the 1970s (McHarg and Sutton, 1975; McHarg, 1996). The planning concept was to determine building densities and land use based on the hydrologic properties of the soil, that is, permeability. This concept was achieved by preserving land with high soil permeability as open space and using land with low soil permeability for commercial or residential developments (McHarg, 1996). Despite the lack of rigorous scientific evaluations, this ecological planning approach is regarded as successful based on extreme storm events. The Woodlands survived the one-hundred-year storms in 1979 and 1994 with little property damage, while Houston, 50 km to the south, was severely flooded in both events (Girling and Kellett, 2005).

This study investigated: (1) the extent to which The Woodlands development adhered to McHarg's original plans overtime, and (2) the potential impact of different planning approaches (conventional low-density, clustered high-density, and The Woodlands approaches) on stormwater. "What if" land-use scenarios for The Woodlands were created to reflect different planning approaches. Furthermore, development was designated onto different soil types (e.g., sandy or clay soils) to assess McHarg's concept. A homogeneous forest land-use scenario was used as the baseline condition to represent The Woodlands prior to any development (Soil Conservation Service, 1972). Scenarios were compared by using the Automated Geospatial Watershed Assessment (AGWA) tool that simulates streamflow (Hernandez et al., 2005).

2.3 Materials and Methods

2.3.1 Study Site

The study area is the Panther Creek watershed, in which the majority of The Woodlands is located. The Panther Creek watershed lies completely within Montgomery County, Texas, and is a sub-watershed of the Spring Creek watershed, U.S. Geological Survey (USGS) hydrologic unit code 12040102 (Fig. 2-1). Interstate Highway 45 runs parallel to The Woodlands to the east, and is a major transportation corridor connecting Houston (50 km away) to the south and Dallas/Fort Worth (340 km away) to the north.

The Panther Creek watershed boundary was delineated using a user-defined outlet located at the confluence of the Panther Creek and the Spring Creek (Bedient et al., 1985). The drainage area of the watershed is 94.2 km^2 . The linear length of the watershed is approximately 37 km from the headwater to the outlet. The average slope of the watershed is 0.15 m km^{-1} . There are two USGS gauge stations on the main channel of the Panther Creek: station #08068450 and station #08068400. The average annual rainfall in this region is 840 mm. However, annual hurricane visitation often generates intense rainfall in single events, which are almost equal to the average precipitation and cause widespread flooding.

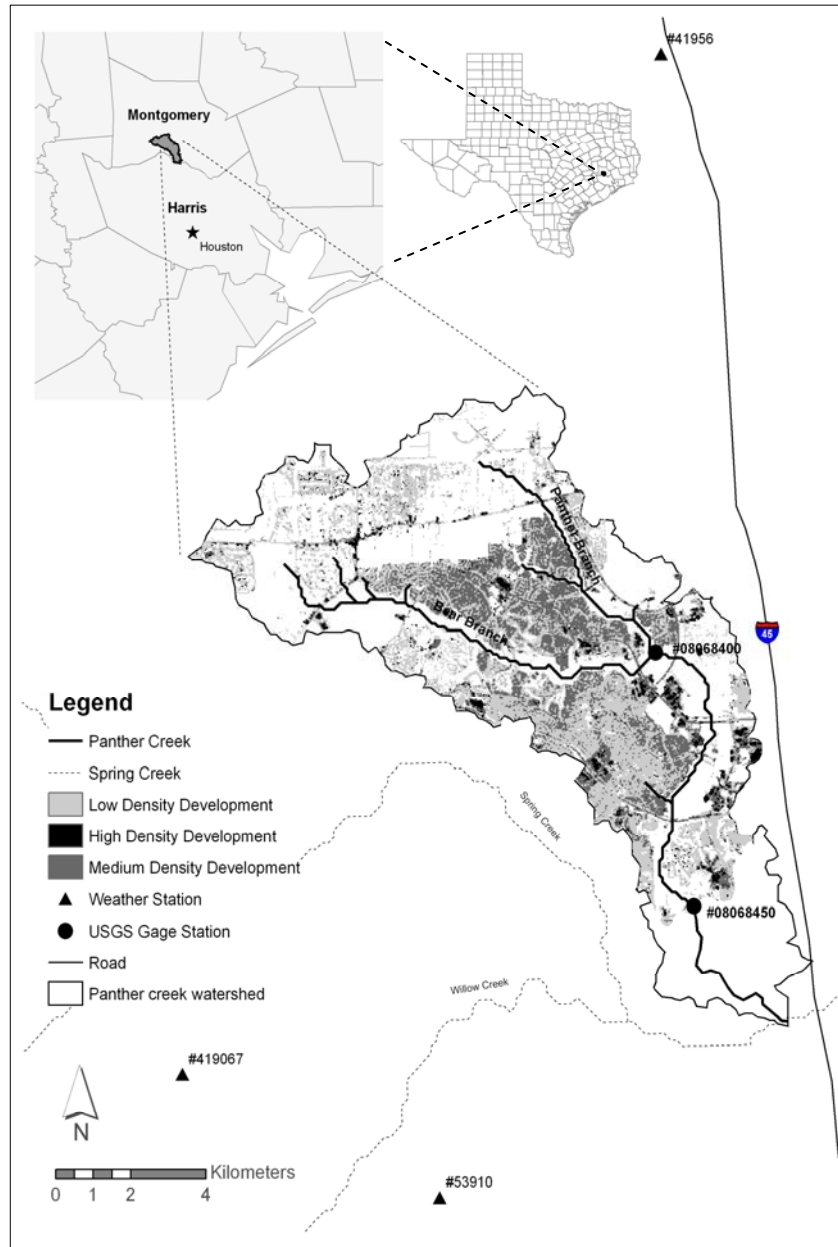


Fig. 2-1. Panther Creek watershed development and stream network. According to the USGS, residential development densities are categorized by fraction total impervious area (FIMP): (1) residential low density, FIMP=0.12, (2) residential medium density, FIMP=0.38, and (3) residential high density, FIMP=0.6.

2.3.2 Data

Stream flow data from both USGS gauge stations on the Panther Creek during the water years of 1999 – 2006 were used for analysis. Historical weather data (e.g., precipitation and temperature) were obtained from the National Climate Data Center website (NCDC). Thiessen polygon method was used to calculate precipitation for the Panther Creek watershed. Three weather stations (COOPID #411956, COOPIN #419067 and WBANID #53910) were identified according to the Thiessen method. Data from 1999 to 2006 were collected from these three stations. River reach files of the Panther Creek watershed were downloaded from the National Hydrograph Dataset (NHD) website, and topographical data of this watershed were obtained from the USGS National Map Seamless Data Distribution System (USGS). Land-use information of four years (1984, 1996, 2001 and 2005) was obtained from various national land-use datasets. The soil dataset used in this study was the high-resolution (1:24,000 scale) Soil Survey Geographic (SSURGO) dataset developed by the Natural Resources Conservation Service (NRCS).

2.3.3 Measurement

2.3.3.1 Land-use change and development location

The first set of analyses evaluated to what extent The Woodlands development followed McHarg's ecological plans to preserve more lands with permeable soils than those with less permeable soils. The land-use and land-cover change was examined in

the watershed of four years (1984, 1996, 2001 and 2005). Furthermore, the land-use and land-cover grids were overlaid with soil grids to quantify the percentages of impermeable cover on each soil group. Soils in the watershed were grouped according to their hydrologic properties defined by the U.S. Department of Agriculture (USDA, 2002). There are four hydrologic soil groups: A, B, C and D. A soils are sandy and loamy sand soils; B soils are sandy loam and loam soils; C soils are silt loam and sandy clay loam soils; D soils are clay loam, silty clay loam and clay soils. A soils have the highest infiltration rate. B and C soils have the moderate infiltration rates. D soils have the least infiltration rate.

2.3.3.2 Simulated land-use scenarios

The second set of analysis assessed the potential impact of different planning approaches on streamflow. Fig. 2-2 shows five hypothetical scenarios which were based on, or contrary to McHarg's planning approach. When allocating development in the watershed, the general trend of The Woodlands development in history and also considered the soil patches were considered. Historically, the first village started downstream of the Panther Creek, and development evolved along the creek to the north. When developing Scenarios 2-5, the general trend of development from downstream to upstream was maintained. This procedure minimized the possibility of assigning development randomly in the watershed. Detailed procedure of scenario development is given below.

- *Scenario 1: forest baseline scenario*

—Developed lands (e.g., residential and commercial) were reversed back to evergreen forest, while other natural land-covers were maintained (e.g., wetland, herbaceous, etc.)

- *Scenario 2: high density clay soil scenario*

—High-density development occurred on C and D soils. The cluster compact development plan preserves a large amount of open space for stormwater detention and infiltration (Center for Watershed Protection, 1994). This was the expected optimal condition.

- *Scenario 3: high density sandy soil scenario*

—High-density development was used and occurred on A and B soils.

- *Scenario 4: low density clay soil scenario*

—Low-density development was used and occurred on C and D soils.

- *Scenario 5: low density sandy soil scenario*

—Low-density development was used and occurred on A and B soils. Scenario 4 and 5 presented conventional low-density development ubiquitous in the U.S. (e.g., Houston), and Scenario 5 was the expected worst case scenario among the five.

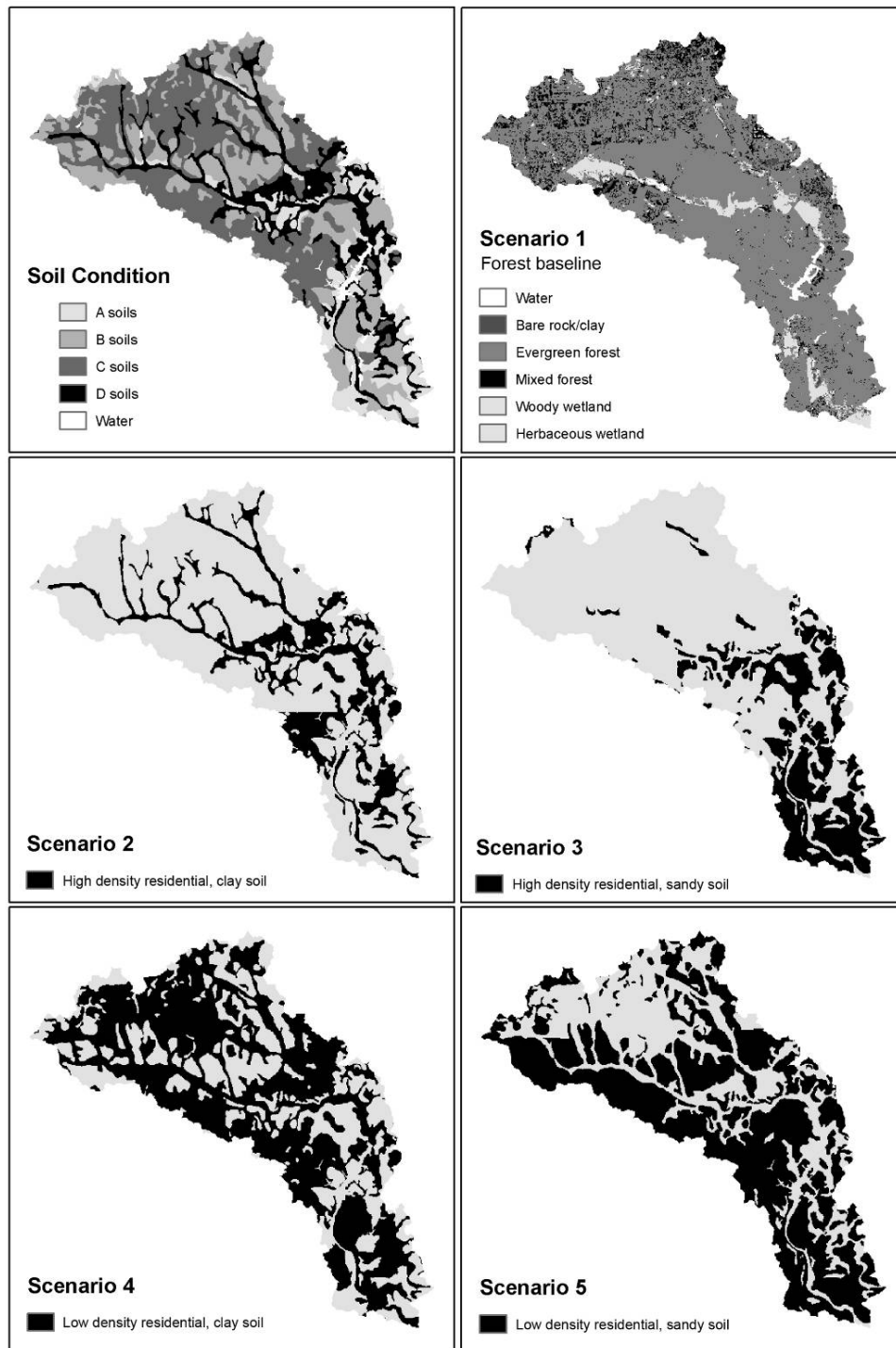


Fig. 2-2. Land-use scenarios 1-5 and watershed soil conditions A-D.

The Woodlands 2005 land-use conditions were used to define the impervious cover area in the watershed and created Scenarios 2-5 that maintained the same imperviousness as the 2005 condition. Impervious cover presents an important variable affecting watershed runoff. This variable was held constant so that scenarios would be compared. Developed area, primarily residential and commercial land-uses, was used as a substitute for impervious cover.¹

According to the USGS, residential and commercial land-uses present a range of impervious cover percentages. The impervious cover ratio index was created to control the total impervious area (Table 2-1). This index made it possible to change from one density to another, and from one approach (e.g., low-density) to another (e.g., high-density). Firstly, the lowest median value (that of the low-density) was assigned as the baseline value, which was a ratio index of one. Secondly, the ratios for two other densities were calculated based on their median values. For example, it will require 2.6 acres of low-density residential land to match the same impervious area of one-acre of high-density residential land. Finally, all residential and commercial land-uses were changed to high-density residential land in the *high density clay soil scenario* (Scenario 2) and in the *high density sandy soil scenario* (Scenario 3). Similarly, all residential and commercial land-uses were changed to low-density residential land in the *low density clay soil scenario* (Scenario 4) and in the *low density sandy soil scenario* (Scenario 5).

Scenarios 2 and 3 present a high-density residential dominated land-use while a large amount of green space is preserved from development. Scenarios 4 and 5 employ the conventional Houston low-density development method where low-density residence

¹ Developed area accounts for 49% of the Panther Creek watershed. See Fig. 2-3.

is promulgated everywhere in the watershed. Thus less green space is preserved in Scenarios 4 and 5 compared to Scenarios 2 and 3. The *forest baseline scenario* (Scenario 1) represents the watershed remaining as forest prior to any development (SCS, 1972). It serves as the baseline condition for the other four scenarios. The 2005 land-use plans were reclassified to create this scenario, whereas the anthropogenic land-uses (e.g., residential and commercial) were turned into forests.

Table 2-1

Impervious cover ratio index

Land Use	Impervious % Range	Median	Ratio
Residential low density	20-49	35	1.0 (baseline)
Residential medium density	30-79	55	1.6
Residential high density	80-100	90	2.6
Commercial/industrial/transportation	80-100	90	2.6

2.3.3.3 Automated Geospatial Watershed Assessment simulation

Automated Geospatial Watershed Assessment (AGWA) (Hernandez et al., 2005; Miller et al., 2007), a multipurpose hydrologic tool for watershed modeling, was used to evaluate the hydrologic consequences of urban development in the watershed.

Embedded in ArcGIS interfaces, AGWA combines two extensively used watershed hydrologic models: the Soil and Water Assessment Tool (SWAT; Arnold et al., 1994); and the Kinematic Runoff and Erosion model (KINEROS; Smith et al., 1995). SWAT is a hydrologic and water quality model for long-term watershed simulations. Although it is widely used in agriculture dominated land uses (Srinivasan and Arnold, 1994), SWAT

could also be used for urban watershed modeling (Fohrer et al., 2000). KINEROS is an event-driven model designed to simulate runoff and erosion for single storm events in small watersheds. In KINEROS, a network of channels and planes is used to represent a watershed and the flood routing is based on the kinematic wave method (Smith et al., 1995).

For the purpose of this study, Curve Number (CN) was the main parameter calibrated in the SWAT model to reflect the 2005 land-use and land-cover conditions. In the KINEROS model, Manning's roughness coefficient (Manning's N) and CN were the parameters calibrated. After model calibration and validation, five land-use scenarios were simulated using SWAT and KINEROS. In SWAT, the average runoff depths of the watershed from 2001 to 2005 were simulated. In KINEROS, the Soil Conservation Service's rainfall frequency maps (SCS, 1986) were used to generate 24-hour storm events of four return-periods (10, 25, 50 and 100 years).

In the SWAT model, each unique combination of land-use and soil-type will generate a Hydrologic Response Unit (HRU). Superimposing various land-use types onto different soil patches will generate runoff quantities for comparison. In addition, each HRU is directly related to a curve number (CN) (Srinivasan and Arnold, 1994). The CN method was developed by NRCS, and is an infiltration and runoff model widely used among engineers and watershed managers. The composite CN was calculated for watershed in each scenario.

The composite watershed CN was calculated as:

$$CN_{composite} = \frac{\sum_i A_i CN_i}{\sum_i A_i}$$

where A_i is the area of sub-watershed i ; CN_i is the CN of sub-watershed i .

The SWAT model simulation was run for a five-year period (2001–2005) following a two-year warm-up period (1999-2000). The warm-up period was to establish appropriate initial conditions for soil water storage. Then the five-year period was divided into two parts to perform model calibration (2001–2003) and validation (2004–2005). USGS measured data were used for calibration. In the calibration process, a baseflow program was used to screen the base flow component in the USGS measured flows in order to increase the SWAT model efficiency (Arnold and Allen, 1999). The SWAT model efficiency was assessed by two criteria. The first criterion is the Nash and Sutcliffe coefficient (Nash and Sutcliffe, 1970), expressed as:

$$E = 1 - \frac{\sum (Q_{obs} - Q_{sim})^2}{\sum (Q_{obs} - Q_{mean})^2}$$

where E is the coefficient of efficiency; Q_{obs} is the observed streamflow (mm); Q_{sim} is the simulated streamflow (mm); and Q_{mean} is the mean observed streamflow during the evaluation period. E varies from minus infinity to one, with one representing a perfect fit of the model. The second criterion is regression analyses. Regression analysis for calibration shows how well the simulated data match the measured data. Regression analysis for validation shows how accurately the calibrated model predicts the subsequent measurements.

2.4 Result

2.4.1 Land Use Change and Development Location

The Panther Creek watershed (The Woodlands) has experienced rapid urbanization since its opening in 1974. By 2005, the original forest-dominated natural landscape has shifted to residential-dominated land-use, which occupied nearly half of the watershed (Fig. 2-3). According to USGS, there were 22 land-use categories in the land use land cover (LULC) datasets. For simplicity, we further grouped them into seven categories: (1) water (open water, woody wetlands and emergent herbaceous wetlands), (2) urban (low density residential, medium density residential, high density residential, and commercial/industrial/transportation), (3) forest (deciduous forest, evergreen forest and mixed forest), (4) agriculture (pasture/hay, row crops and small grains), (5) grassland, (6) grasslands/herbaceous, shrubland, urban/recreational grasses, and (7) others (bare rock/sand/clay and transitional).

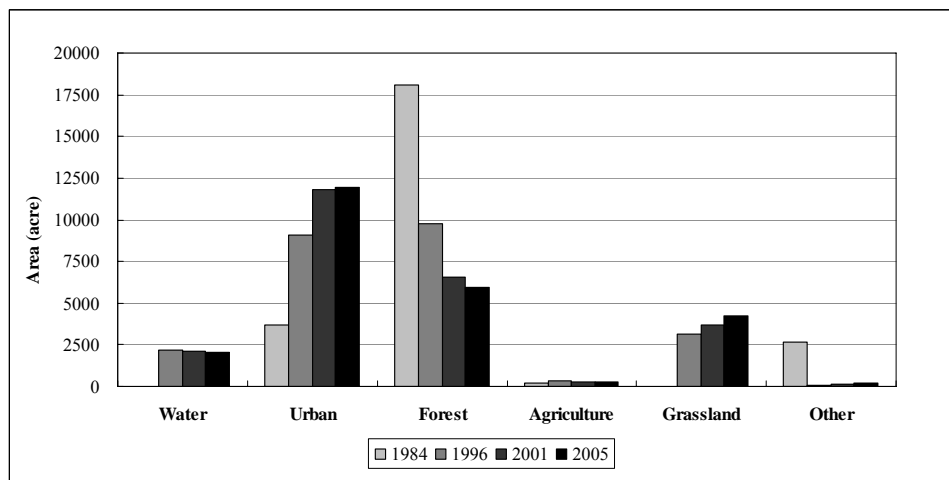


Fig. 2-3. Land-use and land-cover distribution in the Panther Creek watershed (The Woodlands).

Table 2-2 lists development area on each soil group and the percentage of developed area out of the total area of that soil group. It was found that for each phase of the development, more development occurred on permeable soils (A and B soils) than on less permeable soils (C and D soils). This is on the contrary to McHarg's planning concept to preserve permeable soils for stormwater infiltration.

Table 2-2

Development location on different soil groups in the Panther Creek watershed (The Woodlands) during three development phases

	Development Area on Different Hydrologic Soil Group							
	A		B		C		D	
Total area (acre)	1265		2130		1146		2322	
	Acre	%	Acre	%	Acre	%	Acre	%
Phase I (1972-1984)	463	37	707	33	123	11	463	20
Phase II (1985-1996)	512	40	861	40	281	25	898	39
Phase III (2001-2005)	585	46	1276	60	525	46	1059	46

Further investigations of the soil distribution in the watershed and development phases (Fig. 2-4) reveals an interesting finding. In Phase I, more development occurring on permeable soils was because the majority soil groups are A and B soils in the lower reaches of the watershed. In Phase I development, McHarg's concept was strictly followed (McHarg and Sutton, 1975; McHarg, 1996). In Phase II development, there are more C and D soils than A and B soils in the middle reaches of the watershed. It was evident that A and B soils were well preserved and land with much higher percentages of

C and D soils were developed. In Phase III development, however, the development presented little consideration on preserving permeable soils. This can be attributed to the change of The Woodlands ownership in 1997, after which McHarg's concept was largely abandoned.

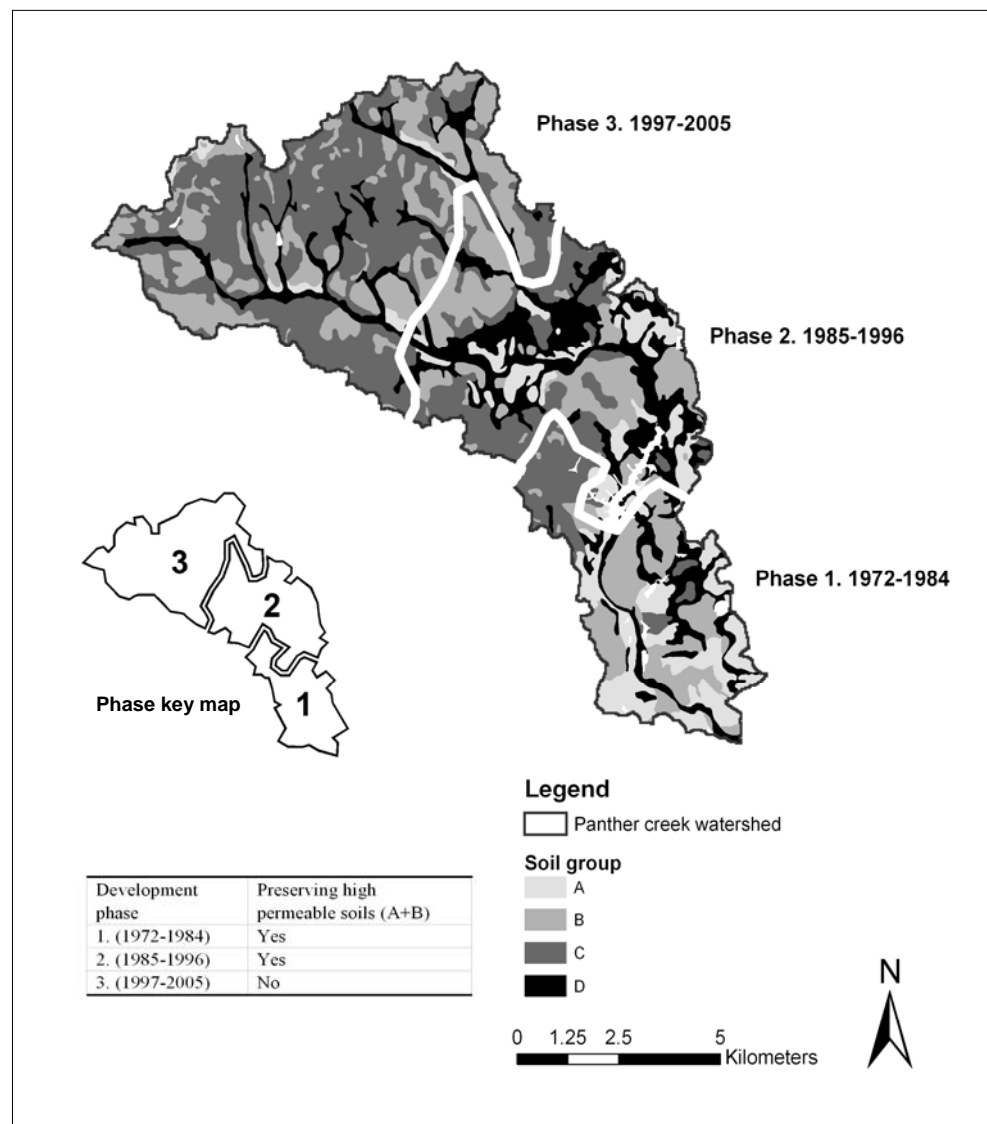


Fig. 2-4. Soil distribution in the Panther Creek watershed (The Woodlands) and three development phases.

2.4.2 SWAT Simulation

2.4.2.1 CN modeling

SWAT model calculated the watershed CNs for the five scenarios and actual conditions in four different years (Table 2-3). Anthropogenic land uses (e.g., residential and commercial) were grouped together as urban development. The simulation yielded expected results, in which the high density scenarios (Scenarios 2 and 3) have lower CNs than the low density scenarios (Scenarios 4 and 5). It was also found that The Woodlands actual development condition in 2005 was similar to the worst case scenario (Scenario 5, low density development on sandy soils) simulated in the watershed modeling. Both CNs of the 2005 condition and the worst case scenario were 80.4 and 80.8, respectively. We did not expect such a result and details are discussed in the Discussion section.

Table 2-3

Land-use scenarios and observed land-use conditions in the Panther Creek watershed
(The Woodlands)

Hypothetical Scenarios	% Urban	Watershed CN	Data ^a
1. Forest baseline	0	66.9	HGAC
2. High density clay soil	49	73.3	HGAC
3. High density sandy soil	49	74.4	HGAC
4. Low density clay soil	49	79.0	HGAC
5. Low density sandy soil	49	80.8	HGAC
Observed Conditions	% Urban	Watershed CN	Data ¹
1984	26	71.6	EPA
1996	37	72.1	NLCD
2001	48	77.6	HGAC
2005	49	80.4	HGAC

^a The land-use and land-cover datasets are 1984 EPA GIRAS data (1:250,000 scale), 1996 National Land Cover Dataset (NLCD) (1:24,000 scale), and 2001 and 2005 Houston Galveston Area Council (HGAC) coastal data (1:24,000 scale).

2.4.2.2 Calibration and validation

SWAT calibration shows promising results in The Woodlands watershed modeling. As shown in Fig. 2-5, USGS observed results can be reasonably predicted by the SWAT model after calibration. The Nash and Sutcliffe (N-S) model efficiencies also confirm the calibration and validation results (Table 2-4). According to Van Liew and Garbrecht (2003), simulation with yearly data is considered “good” when the Nash and Sutcliffe (N-S) efficiencies is greater than 0.75. When using monthly data, values of N-S efficiencies greater than 0.52 are considered as good results (Srinivasan et al., 1998). The calibrated SWAT model was used for watershed modeling on five hypothetical scenarios.

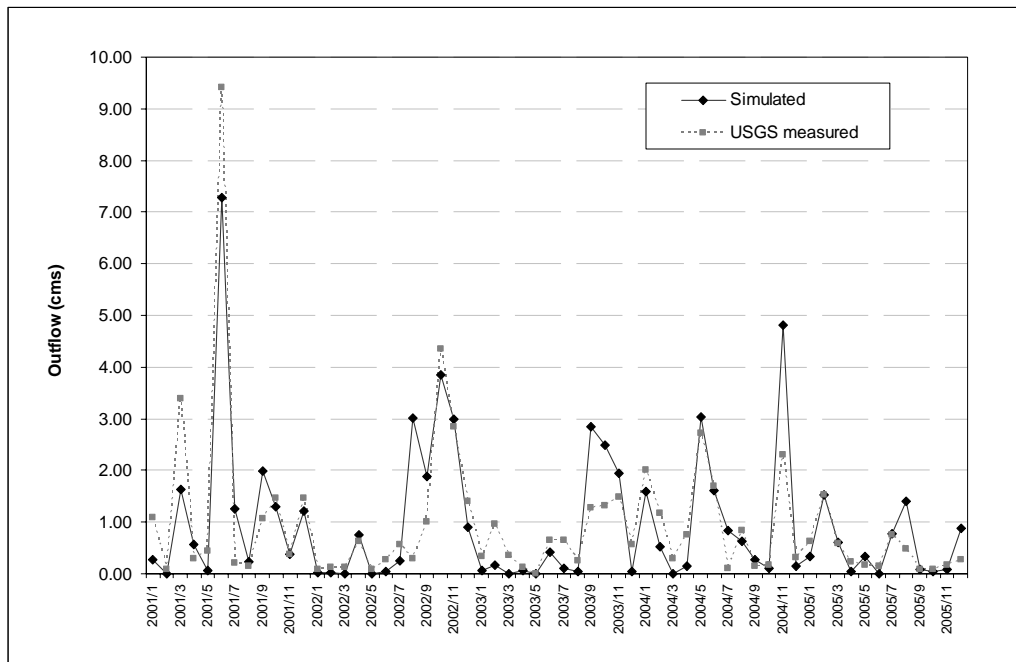


Fig. 2-5. Simulated and observed surface runoff for the calibration and validation periods at USGS gauge station #08068450.

Table 2-4

Model efficiency and statistics from Ordinary Least Square regression analyses for the calibration and validation periods

USGS Gauge	Nash Sutcliffe Coefficient				R^2	
	Calibration		Validation		Calibration	Validation
	(monthly)	(yearly)	(monthly)	(yearly)	(monthly)	(monthly)
#8068450	0.76	0.97	0.63	0.92	0.76	0.70
#8068400	0.71	0.79	0.59	0.98	0.72	0.58

Note: Linear regression analysis, $Y=a + bX$; independent variable X is precipitation (mm), dependant variable Y is streamflow (m^3s^{-1}).

2.4.2.3 Stormwater runoff

Using the observed weather data (2001 to 2005), the SWAT model simulated the annual surface runoff and sediment yields for the five land-use scenarios and the results are presented in Fig. 2-6. As expected, the high-density scenarios generated the least amounts of runoff and sediment, while the low-density scenarios generated the most for both. For the *low density sandy soil scenario* (Scenario 5), where A and B soils were used for development and became impervious covers, the values were the highest. It was noteworthy that all land-use scenarios produced higher runoff compared with the forest conditions. On average, high-density scenarios generated around 40-50% more runoff than the forest condition, and low-density scenarios increased these values to around 90-100%. However, the differences between the two soil group were not as pronounced as the differences between the two density groups.

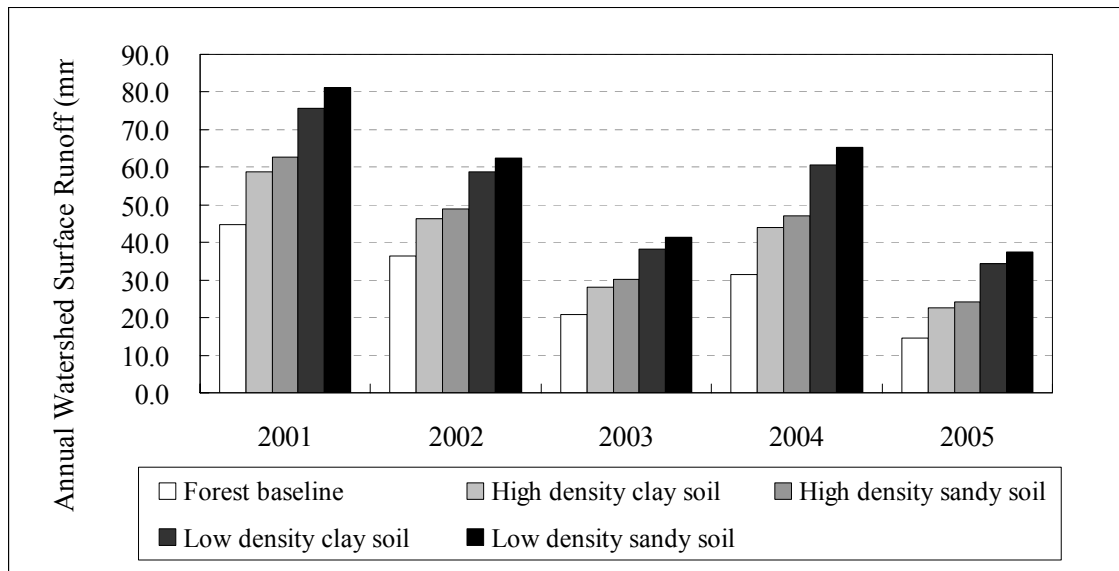


Fig. 2-6. Simulated annual surface runoff of five land-use scenarios.

Table 2-5 shows the average values (2001 to 2005) of the watershed outputs. The trend was evident that surface runoff increased as development density decreased, where situations became worse when A and B soils were paved over. Likewise, a similar trend was predicted that less aquifer recharge and more sediment loading were expected when low-density development spread in the watershed. From the *forest baseline scenario* (Scenario 1) to the low-density development scenarios (Scenarios 4 and 5), sediment loading and surface runoff almost doubled, whereas aquifer recharge reduced to less than 50% of the forest condition.

Table 2-5

Simulated watershed outputs, average of year 2001-2005

Scenario	Surface Runoff (mm)	Total Aquifer Recharge (mm)	Total Sediment Loading (Ton/ha)
1. Forest baseline	26.7	38.2	0.006
2. High density clay soil	35.9	29.6	0.008
3. High density sandy soil	38.3	27.5	0.008
4. Low density clay soil	47.8	19.3	0.011
5. Low density sandy soil	51.4	15.8	0.011

Similar to the results in Fig. 2-6, Table 2-5 shows that the differences of watershed outputs between the two density groups were larger than the differences between the two soil group. It was also important to note that these values were averaged values for the whole watershed. If multiplied by the watershed area (941.6 km²), for instance, the *low density sandy soil scenario* (Scenario 5) will generate 2,343,612 m³ runoff and 47 tons sediments more than the *forest baseline scenario* (Scenario 1) could have on a yearly basis.

2.4.3 KINEROS Simulation

2.4.3.1 Peak flow

Rainfall return frequencies of 10-yr, 25-yr, 50-yr and 100-yr were simulated and presented in Fig. 2-7. As expected, the high density scenarios—*high density clay soil scenario* (Scenario 2) and *high density sandy soil scenario* (Scenario 3)—generated lower peak discharge than the low density scenarios—*low density clay soil scenario*

(Scenario 4) and *low density sandy soil scenario* (Scenario 5)—for all the four frequencies. In addition, the differences between the two density scenarios were not substantial during small rainfall frequencies (i.e., 10 (not shown) and 25-yrs). But the differences became more pronounced as the rainfall frequency decreased (i.e., 50 and 100-yrs). The *low density clay soil scenario* (Scenario 4) and the *low density sandy soil scenario* (Scenario 5) could create a peak discharge around *nine* times of the *high density clay soil scenario* (Scenario 2) and the *high density sandy soil scenario* (Scenario 3) could have during a 100-yr storm.

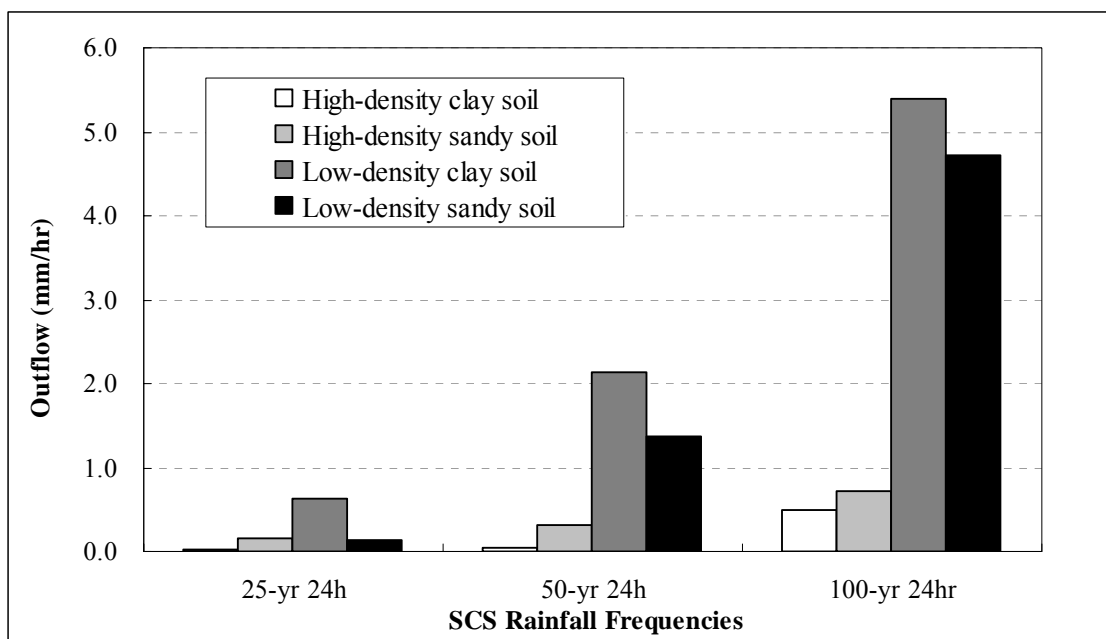


Fig. 2-7. Simulated watershed peak discharges of four land-use scenarios during three rainfall frequencies.

Similar to the SWAT results, the differences between the two soil groups were less, compared with the differences between two density groups. The variations within

each density group decreased as the storm frequencies decreased. However, the differences of peak discharges between the high density scenarios were large. During a 100-yr storm, the *high density sandy soil scenario* (Scenario 3) generated around 50% more peak discharge than the *high density clay soil scenario* (Scenario 2). During smaller storms (25 and 50-yrs), the *high density sandy soil scenario* generated around six times more peak discharge than the *high density clay soil scenario*. Finally, it was unexpected that the *low density sandy soil scenario* (Scenario 5), where A and B soils were paved over, generated less peak discharge than the *low density clay soil scenario* (Scenario 4), which preserved A and B soils for stormwater infiltration.

2.4.3.2 Peak discharge spatial distribution

The spatial patterns of peak discharge at a 100-yr frequency are presented in Fig. 2-8. Peak discharges were higher in urbanized sub-watersheds than sub-watersheds that remain natural conditions. In addition, peak discharges increased as the percentages of development increase. Peak discharge patterns in Fig. 2-8 resembled the land-use distributions in Fig. 2-2. Similar peak discharge patterns were found in other storm frequencies (10, 25 and 50 yrs) but the variations between sub-watersheds became less exaggerated as storm frequencies increased.

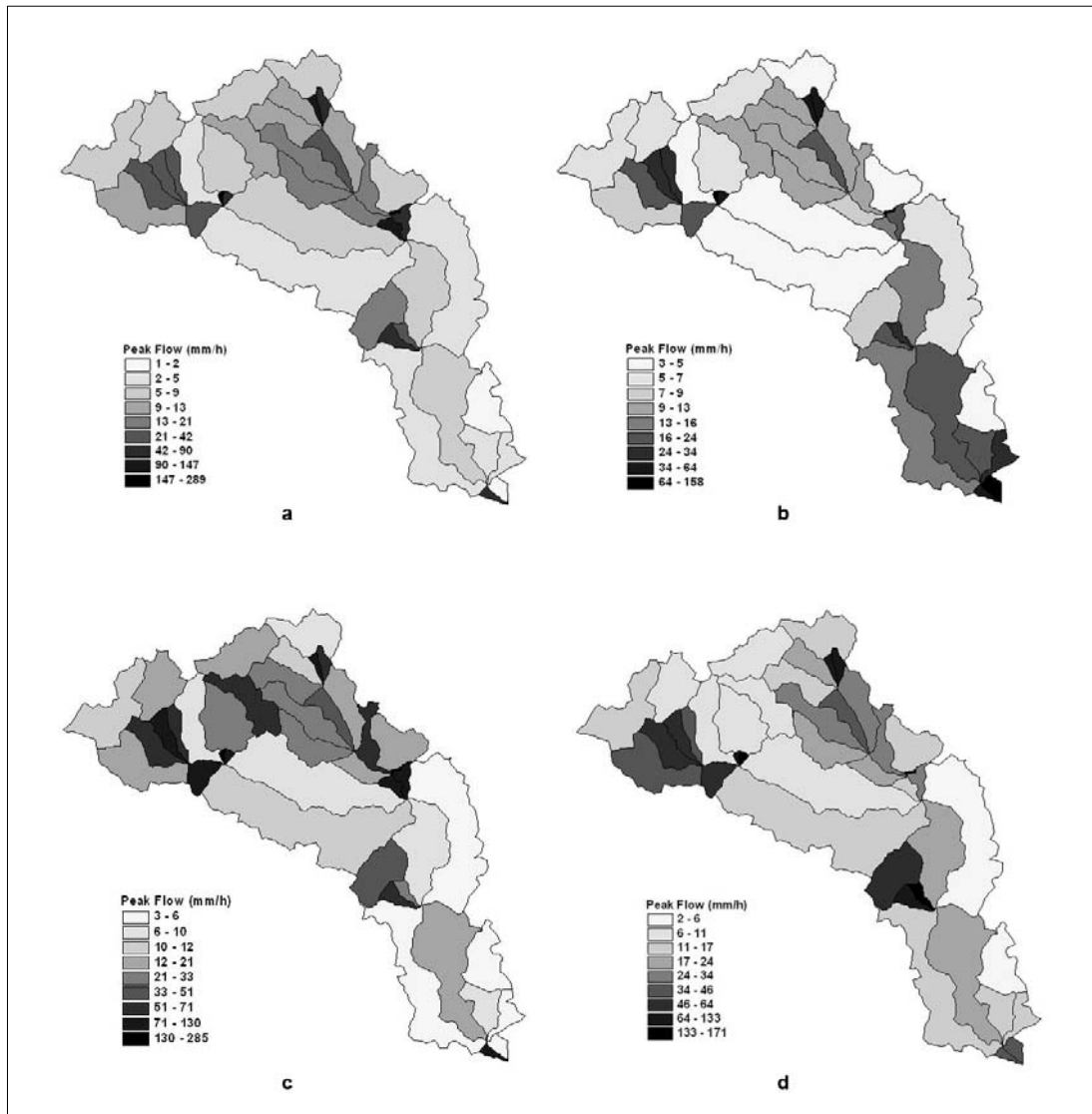


Fig. 2-8. Spatial distribution of peak discharge during 100-yr storms. (a) high density clay soil scenario (Scenario 2), (b) high density sandy soil scenario (Scenario 3), (c) low density clay soil scenario (Scenario 4), and (d) low density sandy soil scenario (Scenario 5).

2.5 Discussion

These results indicate that The Woodlands land-use conditions worsen compared with what the original McHarg plans proposed. The 2005 CN (80.4) is slightly lower than that of the *low-density residential sandy soil* scenario (80.8), the worst case scenario in this study. This value is also as high as that of the conventional quarter-acre single family residential land-use (USDA, 2002). Unfortunately, in Phase I and Phase II development, soils with good infiltration capacities were not given first priority in the community plans. The land-use land-cover changes show that after The Woodlands ownership was sold in 1997, more development occurred on A and B soils than on C and D soils. This is contrary to McHarg's original plan.

Development density plays an important role in determining CNs and watershed runoff. The SWAT and KINEROS models further suggest that during small rainfall, development density is a more important factor than development location per soil permeability. However, during large rainfall, development location per soil permeability is an important factor within each density group. Notice that the total impervious cover is maintained constant for scenarios. The differences between scenarios are development density and location. Watershed runoff volume increases around 35% for high-density scenarios and around 85% for low-density scenarios when compared to the forest baseline condition. Likewise, sediment yields increase around 30% and 80% for high- and low-density scenarios, respectively. However, much lower differences are observed within the groups of the high- and low-density scenarios, with the maximum of less than 10%.

The results are consistent with previous studies on the relationship between development densities and watershed outputs (Hammer, 1976; Schueler, 1994; Stone, 2004). Schueler (1994) reported that compact development could reduce site imperviousness by 10-50% and yield less sediment than a dispersed impervious surface. Our results further demonstrate that even when the total imperviousness is held constant, high-density compact development generates less than 40% runoff compared to low-density development. The Woodlands watershed impervious cover area reached 15% in 1984 and 49% in 2005. Compared to “typical development” in Houston which often increases peak flows by 180%, flow in The Woodlands will increase only 55% according to a simulation study done in the 1970s (Spirn, 1984). This is consistent with these results which forecast the increase in runoff of around 50% at maximum for high-density development and 100% for low-density development.

Besides density, the other focus of this study was development location, that is, the best place to allocate development by soil type. The scenarios generated were not intended to be real community plans as in daily practice, but rather, to provide optimum and worst case scenarios which were either based on, or contrary to McHarg’s approach. SWAT model presents the long-term watershed outflows which differ slightly (7% to 8%) between the two options in both density groups. In other words, development on *clay* or *sandy* soils does not yield much difference in the long-term watershed outflow. However, the differences become extraordinary in extreme storms as shown by the KINEROS model. In a 100-yr storm, the *high density sandy soil scenario* (Scenario 3) could generate around 50% more peak discharge than the *high density clay soil scenario* (Scenario 4).

In short, for long-term watershed runoff and during small rainfall events, development density is a more prominent factor than development location. However, in extreme rainfall events (e.g., 50 and 100-yrs), the development location per soil permeability is an important planning consideration. Plans that preserve high permeable soils are less prone to flooding, compared with plans that develop on those soils. In summary, the *high density clay soil scenario* (Scenario 2) suggests the best solution among the four development scenarios. The *low density sandy soil scenario* (Scenario 4) and the *low density clay soil scenario* (Scenario 5)—conventional development typically found in Houston area—are the least effective plans in the flooding events.

Another finding corresponds to previous studies is the location of development in the watershed has an influence on peak discharge (Bedient et al., 1985). More A and B soils than C and D soils are located in the lower reaches of the Panther Creek watershed. The research design thus led to more development placed on the lower portion of the watershed in the *high density sandy soil scenario* (Scenario 3) and the *low density sandy soil scenario* (Scenario 5) than in the *high density clay soil scenario* (Scenario 2) and the *low density clay soil scenario* (Scenario 4). Thus different development location caused differences of peak discharges among sub-watersheds. The *low density sandy soil scenario* (Scenario 5), though projected to be the worst case scenario, generated less peak discharges compared with the *low density clay soil scenario* (Scenario 4). This could be attributed to the large open space preserved in the upper reaches of the watershed in the *low density sandy soil scenario* (Scenario 5) that detained large amount of runoff and retarded the momentum of peak discharge when it flowed to the watershed outlet.

Development on a particular soil group may not contribute substantially to peak discharge reduction for the whole watershed, but it will undoubtedly affect the sub-watershed outflows. There are vast differences between each sub-watershed in terms of development densities and soil conditions across the four scenarios. For this reason, comparing peak discharge of each sub-watershed in different scenarios was not possible. However, development density and location are both critical factors especially in significant storm events. Finally, the spatial configuration using spatial metrics, even though recent studies report the spatial distribution of impervious cover can affect stormwater runoff (Alberti and Marzluff, 2004; Rogers and DeFee, 2005; Alberti et al., 2007).

In the broader discussion of development indicators for watershed problems, the Center for Watershed Protection concludes that a watershed is severely impacted when only one-tenth of its area is rendered impervious (Center for Watershed Protection, 1994). Ample studies exhibit consistent results with this finding (Arnold and Gibbons, 1996; Paul and Meyer, 2001). Some recent studies argue that other factors are better indicators than impervious cover alone. For example, Rogers and Defee (2005) found that edge density of road is a better indicator than impervious cover to predict watershed outflows (Rogers and DeFee, 2005). Because the urban drainage systems (curb and gutter, drop inlet, etc) are often installed along the streets, edge density accounts for the channelizing effect. As such, the location of development and particularly on top of which type of soils is another important factor (WMRT, 1973; McHarg and Sutton, 1975; Ferguson, 1991; Ferguson et al., 1994). In SWAT long-term watershed simulation, soil is a minor factor compared with density in predicting runoff and sediment yields.

However, in KINEROS simulation, soil presents a significant factor in runoff prediction during large storms, which is closely related to the flooding issues.

2.6 Conclusions

When integrating urban development into the natural system, planners and landscape architects must seek harmony rather than produce conflict. There are various important factors affecting stormwater runoff including precipitation volume and intensity, time parameters, and soil permeability. The only factor designers can manipulate is ground cover (density, configuration, and surface texture). McHarg's plans for The Woodlands were based on a profoundly simple concept: designers should coordinate densities and land use according to the hydrologic properties of the soils. His plans aimed to maintain the natural levels of percolation and runoff, and minimize urbanization impacts.

These results suggest soils with high infiltration capacities were not given first priority in land preservation in The Woodlands after its ownership was sold in 1997. It is not surprising that McHarg's ecological planning approach has been more effective in stormwater management than the low-density conventional Houston planning approach. Using soil permeability to coordinate development densities and land use presents a viable solution to the flooding problems in community development. This study further suggests that compact high-density development combined with McHarg's approach is the best solution among development approaches compared in this study.

Finally, it is important to reiterate that this study only examined one watershed using snapshots of development conditions of four years. Future study needs to include more samples which present more variations of the watershed conditions. Development in a watershed increases the chance for flooding. The Woodlands current conditions, though of a less quality than originally proposed, are further ahead in promoting a sustainable community development model than conventional solutions (Spirn, 1984; Bedient et al., 1985; Forsyth, 2002; Girling and Helphand, 2003). Even though environmental data, particularly soil data, may cease to be used to determine which location and what proportion of the land is developed, The Woodlands' planning, design, and management presents as excellent example of eco-conscious urban planning for design professionals to consider.

CHAPTER III

**DRAINAGE DESIGNS IN THE WOODLANDS, TEXAS:
COMPARATIVE STUDY OF OPEN SURFACE AND
CONVENTIONAL DRAINAGE SYSTEMS IN COMMUNITY
DEVELOPMENT**

3.1 Synopsis

Conventional urban stormwater collection and conveyance systems such as curb and gutter, drop inlet, and underground piping are known to concentrate stormwater and may contribute to downstream flooding. In contrast, open surface drainage that mimics the natural flow regime is regarded to mitigate development impacts on watershed. A few built examples that used open surface drainage design are earlier villages in The Woodlands, Texas, a town created with Ian McHarg's ecohydrological planning approach. Open surface drainage was used in the first two villages in The Woodlands while conventional drainage was installed in other later villages. The objective of this study is to compare both drainage designs on flood mitigation effectiveness. Two sub-watersheds within The Woodlands which employed different drainage designs were compared. Stream data from the gauge station at the outlet of each sub-watershed were used for analysis. Geographic Information System was used to quantify the development conditions. Correlation analysis was performed using measured precipitation and

streamflow data. Results show that by 2002, developed area in the conventional drainage and open surface drainage watersheds grew 21% and 32%, respectively. Less storm runoff volume was observed in the open drainage watershed than the conventional drainage watershed after development. In addition, the open surface drainage watershed responded to rainfall in a way similar to its pre-development natural forest conditions. The correlations of precipitation and streamflow remained low in both pre- and post-development conditions, indicating strong flood mitigation effectiveness by using open surface drainage. In contrast, in the conventional drainage watershed, the precipitation-streamflow correlations increased enormously after development. The open drainage system presents advantage over the conventional drainage solution in mitigating flood problems in community development.

3.2 Introduction

Conventional urban stormwater collection and conveyance systems such as curb and gutter, drop inlet, underground piping are known to concentrate stormwater and may contribute to downstream flooding (Paul and Meyer, 2001). Conventional drainage solution aims at exiting stormwater as fast as possible and minimizing storage. This system alters the flow regime and transfers stormwater faster than the natural hydrological cycle (Ferguson, 1998; Paul and Meyer, 2001). In urban development, a conventional drainage system is typically installed along the streets and underground. Streets are placed at low elevations and function similar to detention ponds to collect stormwater in rainfall events. This drainage system, however, is vulnerable when urban development exceeds its relatively limited storage capacity (Ellis and Marsalek, 1996). In addition, stagnant water on roads generated in intense rainfall cause safety problems.

In contrast, open surface drainage that mimics the natural flow regime is regarded to mitigate development impacts on watershed. Open surface drainage is often designed as grassed swales pitched with a certain gradient. Grassed swales are placed at low elevations and serve as drainage channels to transport stormwater away from roadways. Roads in this situation are placed at high grounds, minimizing the safety problems.

Dry swale and wet swale are two types of grassed swales that are currently in use. Dry swale facilitates stormwater infiltration, reduces peak discharge and provides water quality treatment (Prince George's County, 1999). Swales with trapezoidal shape and meandering path increase the storage volume and provide a less efficient system than the

channelized pipe system. Wet swale uses natural vegetation growth to perform similar stormwater quantity and quality control as the dry swale (Prince George's County, 1999). If specifically designed, wet swale functions similarly as a bioretention basin. A bioretention swale installed in a conventional residential road in Seattle, Washington, reported a 97 percent runoff volume deduction compared with the pre-construction runoff volume. In some modest rainfall, this bioretention swale produced no runoff (Horner et al., 2002).

Although open surface drainage may provide an alternative to conventional underground drainage in light of the rising flooding problems, very few subdivisions have implemented open surface drainage at a large scale. One of the examples is The Woodlands, Texas, a new town pioneered in open drainage systems under Ian McHarg's ecohydrological planning concepts (WMRT, 1973a; McHarg and Sutton, 1975). The Woodlands survived storms in excess of 100-year levels in 1979 and 1994 (Girling and Kellett, 2005). Despite the lack of scientific evidence, the open drainage system is regarded as an important factor in protecting the community from flooding (Morgan and King, 1987; Galatas and Barlow, 2004).

Open surface drainage was implemented in the early phases of The Woodlands development (Galatas and Barlow, 2004). However, most homeowners did not like the rustic appearance of the open drainage channels. To improve marketability, The Woodlands gradually shifted to conventional drainage practices (Gause et al., 2002; Galatas and Barlow, 2004). Fig. 3-1 shows different drainage systems in The Woodlands before and after 1997. After the conventional system was installed, The Woodlands got flooded in 2000 (NOAA, 2000) and again in 2008 by Hurricane Ike (Madere, 2008).

This study compares the flood mitigation effectiveness of the two drainage systems used in different phases of development.



Fig. 3-1 (a)

Fig. 3-1 (b)

Fig. 3-1. Different drainage systems in The Woodlands.

(a) Open surface drainage system in the first two villages (before 1997)

(b) Conventional underground drainage system in later rest villages (after 1997)

3.3 Study Site

Fig. 3-2 shows the two sub-watersheds in comparison. Watershed #1 (22.3 km²) and Watershed #2 (67.1 km²) comprises the Panther Creek watershed—defined by the U.S. Geological Survey (USGS) gauge station #08068450. The majority of The Woodlands is located within the Panther Creek watershed and lies completely within Montgomery County, Texas. U.S. Highway 45 runs parallel to The Woodlands to the east, and is a major transportation corridor connecting Houston (48 km away) to the

south and Dallas/Fort Worth (338 km away) to the north. In 1972, The Woodlands development started from downstream of the Panther Creek and evolved along the creek to upstream.

It is important to note that Watershed #1 does not constitute a *watershed* in the commonly known watershed definition. Watershed #1 is the Panther Creek watershed excluding Watershed #2. This is a working definition of Watershed #1 for the purpose of this study. Watershed # 1 includes approximately one third of the first village—Village of Grogan’s Mill and the majority of the second village—Village of Panther Creek. Open drainage system was implemented in the first village and part of the second village (Kutchin, 1998; Galatas and Barlow, 2004).

Watershed #2 is defined by the USGS gauge station #08068400. Watershed #2 remained a pine forest when development started in Watershed #1. Four villages—Alden Bridge, Sterling Ridge, Cochran’s Crossings, and Indian Springs villages—are located in Watershed #2. Conventional drainage system was installed in those villages.

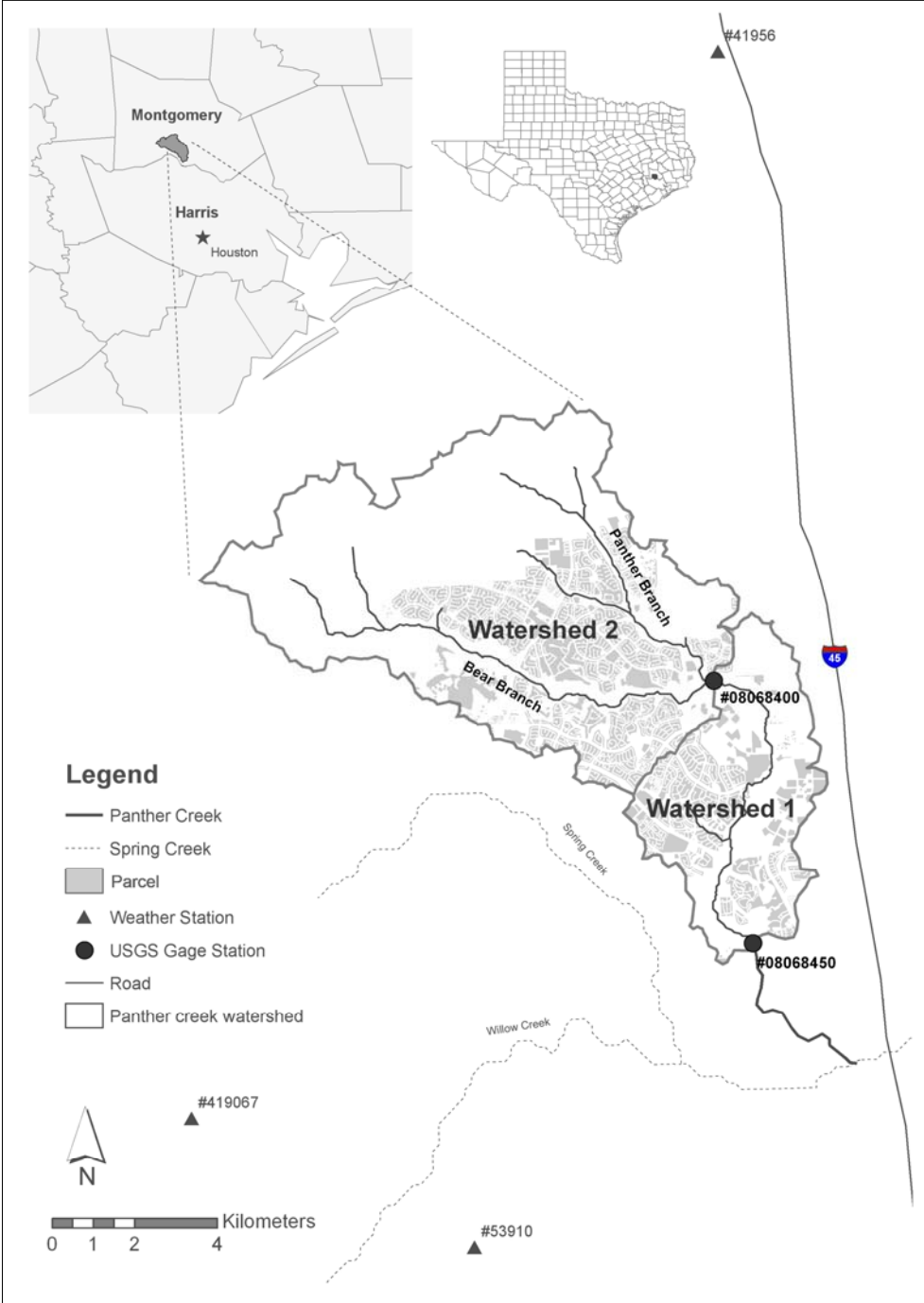


Fig. 3-2. Panther Creek watershed development and two sub-watersheds: Watershed #1 & Watershed #2.

3.4 Data

3.4.1 Impervious Area

Two primary types of impervious area in The Woodlands are residential buildings and roads. Residential development conditions could be reflected by parcel data, which were obtained from Montgomery County Appraisal District. There are various sources to obtain the road information, such as the Texas Natural Resources Information System (TNRIS) and the Texas Transportation Institute (TTI). However, none of them provides the year of road construction. For a particular road, parcels adjacent to it were identified and sorted by year of construction. Then the earliest year was assigned to that road, based on the assumption that the road has to be built for the parcel to be developed (Rogers and DeFee, 2005).

3.4.2 Streamflow

Streamflow data at the USGS gauge stations #08068400 and #08068450 were downloaded from the USGS website. Due to the data availability, data of water years 1975-1976 represented the early phases of development, and data of water years 2000-2002 represented the later phases. According to the USGS definition, a water year is from October through December of the preceding year to September of the current year (i.e., water year 1975= 10/01/1974 - 9/30/1975). For both watersheds, water years 1975-1976 and 2000-2002 were examined.

3.4.3 Precipitation

Historical precipitation data which are coincident with flow data were obtained from the National Climatic Data Center website (NCDC). Thiessen polygon method was used to calculate precipitation for both watersheds. Three weather stations (COOPID #411956, COOPIN #419067 and WBANID #53910) were identified according to the Thiessen method. The area weighted percentage of each station was used to calculate the composite precipitation value for each rainfall event.

Because station WBANID #53910 did not have data records for water years 1975-1976, data from the nearest station COOPID #419067 (less than 7 km away) were used as a substitute. The area weighted percentage of station WBANID #53910 is less than 15% for both watersheds. Therefore, this substitution will not substantially alter the results. For both watersheds, if one station has missing data for a sample day, that day was excluded from analysis. No attempt was made to estimate the missing data.

3.5 Data Treatment

3.5.1 Streamflow

As aforementioned, Watershed #1 is not a watershed in the hydrologic definition. Watershed #1 is a sub watershed located at the lower portion of the watershed defined by gauge #08068450 (see Fig. 3-2). By assuming the flow measured at the upstream gauge #08068400 had no loss in moving downstream, streamflow contributed solely from

Watershed #1 can be calculated by subtracting flow at the downstream gauge #08068450 by flow at the upstream gauge #08068400:

$$Q_1 = Q_{pc} - Q_2 \quad (\text{Equation 1})$$

where Q_1 is the Watershed #1 daily mean streamflow (m^3s^{-1}); Q_{pc} is the daily mean streamflow at gauge #08068450 (Panther Creek watershed outlet) (m^3s^{-1}); and Q_2 is the daily mean streamflow at gauge #08068400 (Watershed #2 outlet) (m^3s^{-1}).

For the same day, flow at the downstream gauge #08068450 is typically greater than flow at the upstream gauge #08068400, a reasonable result as more surface runoff would contribute to downstream areas. Only 19 negative flow values (2.6%; out of 731 samples) in water years 1975-1976 were found and removed from analysis. However, negative flow values were much more frequent in water years 2000-2002. 87 negative values (7.9%; out of 1096) were observed. The reason for more negative values in water years 2000-2002 than 1975-1976 is perhaps because of the 92-hectare Woodlands Lake (built in 1985) that intercepts the stream in Watershed #1. When the lake's water level is low after a long dry period, subsequent rainfall need to refill the lake before the downstream section would flow again. In this sense, the lake intercepts the flow and detains it.

Two flow datasets were prepared for Watershed #1. The first dataset included The Woodlands Lake detention effect, whereas the second dataset excluded this effect. The first dataset included all the data derived from Equation 1 but excluded negative values. This dataset was used for water years 1975-1976 and water years 2000-2002. The second dataset excluded the negative values and further excluded data samples

when The Woodlands Lake intercepted significant amount of flow during its low water level periods. This set of data was only used for water years 2000-2002.

Watershed #2 also has the same stormwater detention issue from a 21-hectare Bear Branch Reservoir built in 1984. This reservoir will affect the measured flow in water years 2000-2002. Similar to Watershed #1, two flow datasets were prepared for Watershed #2. The first dataset was used for both water-year periods, and the second dataset was used only for water years 2000-2002.

3.5.2 Excluding Lake/Reservoir Detention Effect

Since The Woodlands Lake and the Bear Branch Reservoir will intercept stream flows after dry periods, it is imperative to exclude the detention effect in order to evaluate the different drainage systems. Two methods were used to exclude such effect, described in the following sub sections.

3.5.2.1 Method 1

A user defined point at the outlet of The Woodlands Lake was used to delineate the lake contributing area—Sub-watershed #1. Rain falling onto Sub-watershed #1 should contribute to The Woodlands Lake. Similarly, a user defined point at the outlet of the Bear Branch Reservoir was used to delineate the reservoir contributing area—Sub-watershed #2.

Assuming uniform precipitation throughout the watershed (or sub watershed), the depths to fill the lake and reservoir from the normal water level elevations to the

maximum water level elevations were calculated using Equation 2. Variables in Equation 2 are listed in Table 3-1.

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (\text{Equation 2a})$$

$$S = \frac{1000}{CN} - 10 \quad (\text{Equation 2b})$$

$$Q = \frac{A_{\text{lake/reservoir}} \times \Delta H_{\text{lake/reservoir}}}{A} \quad (\text{Equation 2c})$$

According to the original design, $\Delta H_{\text{lake/reservoir}}$ was given the value of 0.3 m (1 ft) in calculation. The calculated precipitation depths were 45.4 mm for Watershed #1 and 41.8 mm for Watershed #2. These values were used to identify sample days when the lake/reservoir was filled by rainfall. 17 samples were identified for Watershed #1 and 56 for Watershed #2. However, it was found that 15 out of the total 17 samples in Watershed #1 and 46 out of the total 56 samples in Watershed #2 have streamflow values twice greater than the base flow value. This result indicated that the lake and the reservoir have reached their maximum water level elevations after rainfall at the calculated depths. Method 1 thus yielded values much greater than what were needed to fill the lake and the reservoir.

Table 3-1

Variables in Equation 2 to calculate precipitation depths needed to fill the lake and the reservoir from the normal water level elevations to the maximum water level elevations in water years 2000-2002

Variable	Value	Unit	Explanation
P	45.4 (calculated)	mm	Precipitation depth needed to fill the lake
	41.8 (calculated)	mm	Precipitation depth needed to fill the reservoir
Q	0.31 (calculated)	mm	Runoff volume of Sub-watershed #1 ^a
	0.23 (calculated)	mm	Runoff volume of Sub-watershed #2 ^a
S	2.7 (calculated)	mm	Potential maximum watershed storage
Curve Number	79	NA	CN used for both sub-watersheds ^b
A _{lake/reservoir}	918,030	m ²	Area of The Woodlands Lake
	205,904	m ²	Area of the Bear Branch Reservoir
$\Delta H_{\text{lake/reservoir}}$	0.3	m	Elevation difference between the normal water level elevation and the maximum water level elevation (lake bank elevation) ^c
	0.3	m	
A	90,444,600	m ²	Sub-watershed #1 area
	26,986,500	m ²	Sub-watershed #2 area

^a Assuming a uniform depth of runoff across the watershed

^b Using the average value of 2001 and 2005 CNs of Panther Creek watershed for approximation. 2001 CN=77.6; 2005 CN=80.4.

^c According to the original design documents (U.S. Army Corps of Engineers, 1982), the normal water level elevation of The Woodlands Lake is 38.1 m (125 feet), and the lake bank elevation is 38.4 m (126 feet). The normal water level elevation of the Bear Branch Reservoir is 49.1 m (161 feet), and the reservoir bank elevation is 49.4 m (162 feet). There is a 0.3 m (1 ft) elevation difference in both water bodies.

3.5.2.2 Method 2

Method 2 used measured precipitation data to calculate the depths and the results were compared with Method 1's. In Method 2, the depths were estimated by averaging precipitation values when corresponding flow values just increased from the base flow value to greater values. Under this condition, the lake/reservoir was just filled up, and no substantial more runoff has been generated by these precipitation events.

Certain criteria were specified to target those precipitation samples. (1) On the first day when precipitation occurs, flow remains close to the base flow (around $0.3\text{m}^3\text{s}^{-1}$). (2) There is no precipitation or only a modest precipitation on the second day. (3) On the second day, flow becomes slightly larger than the base flow.

Following is an example to identify precipitation depth needed to increase the Bear Branch Reservoir to its maximum water level elevation. On September 8, 2000, the flow was $0.08\text{ m}^3\text{s}^{-1}$, lower than the base flow. A 20.7 mm rain occurred on this day. Flow increased to $0.37\text{ m}^3\text{s}^{-1}$ on the second day (Sept. 9) and there was a slight rain (1.4 mm) on this day. Because $0.37\text{ m}^3\text{s}^{-1}$ is slightly greater than the base flow, it was assumed that 20.7 mm is approximately the precipitation depth needed to fill the reservoir from its normal water level elevation to the maximum water level elevation.

Totally, 11 precipitation samples met the above criteria for Watershed #1 and 16 samples for Watershed #2. The average depths from these samples were calculated for each watershed. Finally, the average depths from Method 1 and Method 2 were used to determine the precipitation depths, and the results are presented in Table 3-2.

Table 3-2

Two different methods to calculate precipitation depths needed to exclude the lake/reservoir detention effect

	Rainfall depth (mm)		
	Method 1	Method 2	Avg. method 1 & 2
The Woodlands Lake	45.4	37.9	41.7
Bear Branch Reservoir	41.8	21.2	31.5

3.5.3 Precipitation-Streamflow Data Pair Selection

Precipitation-streamflow data pairs were selected to assess how the watersheds responded to rainfall within different drainage systems. If following a long dry period, streamflow is usually lower than the base flow. The arid soil needs to elevate its antecedent moisture to allow excessive runoff to occur. The precipitation-streamflow relationship was further complicated after 1985 when The Woodlands Lake and the Bear Branch Reservoir stormwater detention facilities were built.

For both water-year periods, precipitation-streamflow data pairs were assessed under two different conditions. For water years 1975-1976, the first condition was the watershed status quo condition. The second condition excluded the watershed's dry periods. Similarly, for water years 2000-2002, the first condition was the status quo condition, and the second condition excluded the lake/reservoir detention effect.

3.5.3.1 Water years 1975-1976 (early phases of development)

In the first condition (status quo), precipitation-streamflow data pairs were selected when precipitation was greater than 0 mm. In the second condition, two criteria were established to exclude the dry periods. (1) If following a long dry period (e.g., a week), rainfall needs to last at least two days, so that rainfall on the first day is able to increase the antecedent soil moisture. If the flow is greater than the base flow on the second day, the second day's precipitation-streamflow data pair becomes eligible. (2) The first day precipitation-streamflow data pair is also acceptable, if flow on the first day is already greater than the base flow when a rainfall event occurs on the first day.

3.5.3.2 Water years 2000-2002 (later phases of development)

Likewise, the first condition (status quo) included precipitation-streamflow data pairs if precipitation is greater than 0 mm. The second condition excluded data pairs influenced by the lake/reservoir detention effect. If meeting one of the following three criteria, the lake or the reservoir is regarded to have reached its maximum storage capacity, and excessive runoff is resulted from subsequent rainfall. (1) Precipitation from the first day must be 41.7 mm to fill the lake or 31.5 mm to fill the reservoir. (2) It is acceptable if the sum of rainfall depths from several consecutive days reaches the specified depths, but flow values during these days need to be consistently greater than the base flow value. (3) It is also acceptable if the first day precipitation is less than the required precipitation, but the flow is greater than the base flow. This indicates the watershed is experiencing a wet period before this rainfall event.

3.6 Analysis

3.6.1 Impervious Area

Developed area was calculated from 1972 to 2002 using GIS. GIS parcel data provide the parcel boundary and location, parcel area, building type, year-built and building square footage. Sorting these data by year-built provides the state of development in the watershed each year. Road surface area was estimated by multiplying the road length with the average width of the roads in the watershed (Rogers and DeFee, 2005). The sum of parcel and road areas provides an approximation of the total developed area in the watershed.

3.6.2 Watershed Runoff Volume

Annual mean runoff depth was calculated for the five water years. Watershed runoff depth (m) is calculated by dividing the total runoff volume (m³) by the watershed area (m²). This method assumes a uniform depth of water falling onto the watershed. In this way the flow volume is standardized and becomes comparable. The runoff depth was calculated using the equation:

$$H = \frac{Q_i \times t}{A} \quad (\text{Equation 3})$$

where H is the watershed annual runoff depth (m); Q_i is the annual mean flow at year i (m³s⁻¹); t is a constant, 31,536,000 seconds, the total second in a year; and A (m²) is the watershed area.

3.6.3 Streamflow Response

A daily streamflow response value was created for streamflow-precipitation data pairs when precipitation is greater than 0 mm (Jennings and Jarnagin, 2002). The streamflow response ($\text{m}^3 \text{s}^{-1} \text{m}^{-1}$) value is calculated by dividing mean daily streamflow ($\text{m}^3 \text{s}^{-1}$) by daily precipitation (m). “Streamflow response value allows for a unified term for the data pair in which changes in streamflow as a result of variations in precipitation could be comparable for historical data” (Jennings and Jarnagin, 2002, p.476). The average annual streamflow response value was calculated for each water year.

3.6.4 Precipitation-Streamflow Correlation

Three sets of correlation analysis were conducted to reflect the watershed characteristics using different drainage systems. The first set of correlation analysis provided an overall comparison of the two watersheds. For water years 1975-1976, correlation analysis was conducted for the watershed status quo condition and the condition in which the dry periods were excluded. For water years 2000-2002, the function of large stormwater detention facilities was assessed.

The second set of correlation analysis was conducted only for water years 2000-2002. The purpose was to compare the flood mitigation effectiveness of different drainage systems together with large stormwater detention facilities. Correlation analysis was conducted on a daily basis for precipitation-streamflow data pairs if precipitation > 0 mm. Precipitation data were further grouped into two categories: >0 mm and >6mm.

The first category (>0 mm) stands for all rainfall events. The second category (>6 mm) includes moderate and large rainfall events (Jennings and Jarnagin, 2002).

The third set of correlation analysis was also conducted only for water years 2000-2002. It aimed at evaluating flood mitigation effectiveness solely provided by different drainage systems. Precipitation categorical analysis was not examined in this analysis because limited samples were available after filling up the lake and the reservoir. Finally, correlation analysis evaluated the daily precipitation-streamflow relationship and the relationship between yesterday's precipitation and today's streamflow (Rogers and DeFee, 2005).

It was found that in water years 2000-2002, Watershed #1 streamflow sometimes did not reach the highest value on the same day when a large rainfall occurred. A peak flow emerged on the second day. However, this phenomenon was less frequently observed in Watershed #2 in this period. This is perhaps because Watershed #1's open drainage system detained runoff and presented a lag time after rainfall, whereas Watershed #2's conventional drainage system discharged runoff efficiently without detaining it.

3.7 Results

3.7.1 Impervious Area

Development conditions in Watershed #1 and Watershed #2 are presented in Fig. 3-3. By the end of 2002, there were 7,326,234 m² (1,810 acres) developed area in Watershed #1 and 14,106,615 m² (3,486 acres) in Watershed #2. These areas accounted for 32% and 21% of Watershed #1 and Watershed #2 areas, respectively. It is important to note that Watershed #1 contains 931,833 m² (203 acres) of The Woodlands Town Center commercial area. This commercial area presents high percentage of impervious cover and will adversely impact the effectiveness of the open drainage system.

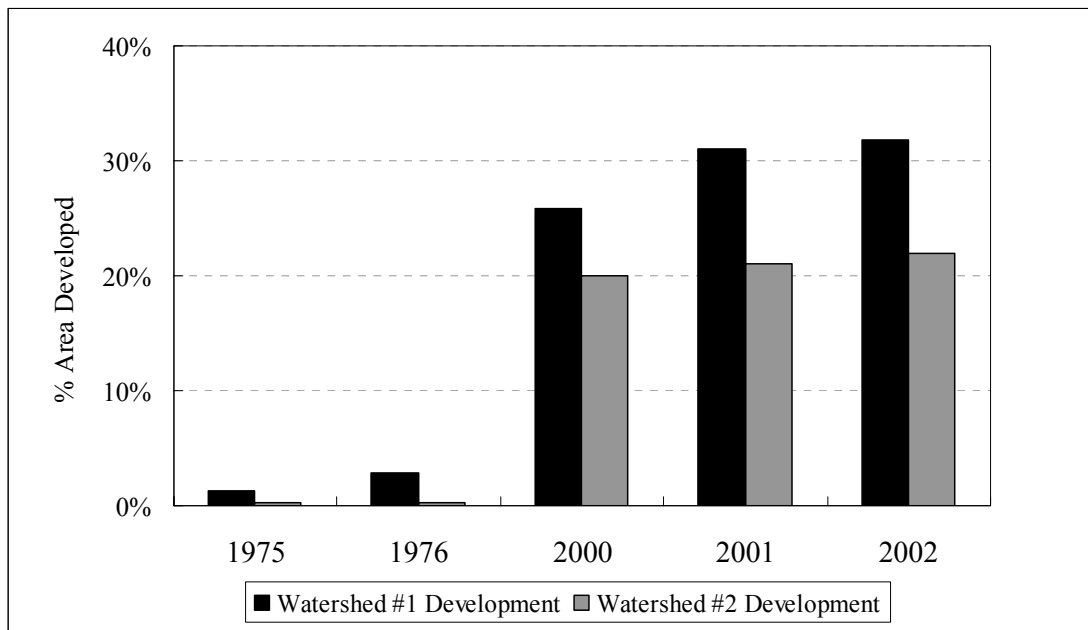


Fig. 3-3. Cumulated percentage of developed area in Watershed #1 (open drainage) and Watershed #2 (conventional drainage).

3.7.2 Watershed Runoff Volume

The annual runoff depths of five specific water years are shown in Fig. 3-4. Two trends emerged in this analysis. The first trend was that Watershed #1 has smaller runoff depth than Watershed #2 in each year examined—meaning less runoff volume has been generated from Watershed #1. The second trend was that a noteworthy increase of runoff depth occurred in Watershed #2 in the later phases of development. In the early phases (1975-1976), Watershed #2's runoff depths were around *three* times of Watershed #1's. However, in the later phases (2000-2002), these ratios increased to *five* to *eight* times.

Because Watershed #2 has a lower percentage of developed area than Watershed #1, more runoff volume from Watershed #2 could be attributed to the differences of drainage designs. In Watershed #1, the open drainage system and The Woodlands Lake detained large amount of water for infiltration and evapotranspiration. Conversely, in Watershed #2, the pipe drainage system facilitates runoff without detaining it—counteracting the detention function provided by the Bear Branch Reservoir.

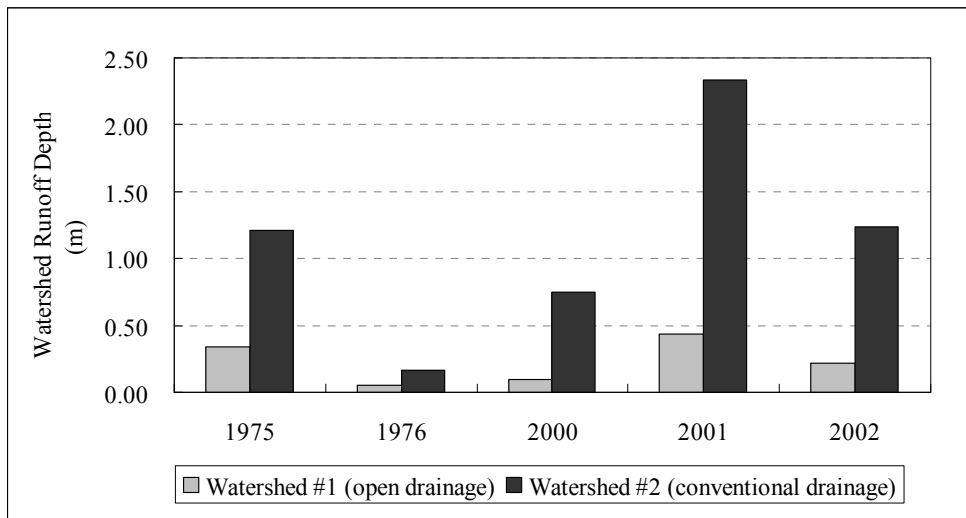


Fig. 3-4. Surface runoff depths of Watershed #1 (open drainage) and Watershed #2 (conventional drainage).

3.7.3 Streamflow Response

Fig. 3-5 shows the streamflow response values and the annual precipitation in the two watersheds. Precipitation values were similar in the two watersheds in each year examined. However, the streamflow response values presented differences in the later phases of development. Likewise, two trends emerged in this analysis. The first trend was that the streamflow response values remained low in the early phases in both watersheds. The second trend was that the value increased at a much greater rate in Watershed #2 than Watershed #1 in the later phases.

In 2002, Watershed #2 streamflow response value was more than *nine* times of Watershed #1—indicating more *flashy* streamflow after development. Given the fact that Watershed #2 has less percentage of developed area than Watershed #1, thus the

conventional drainage system has altered Watershed #2 to be more sensitive in response to rainfall than Watershed #1.

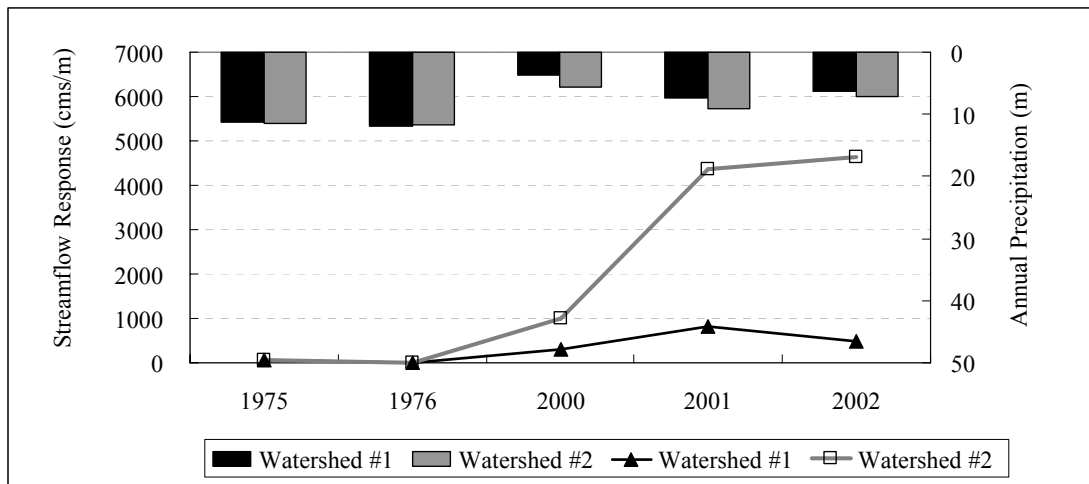


Fig. 3-5. Annual precipitation (m) and streamflow response value ($\text{m}^3\text{s}^{-1}\text{m}^{-1}$) of Watershed #1 (open drainage) and Watershed #2 (conventional drainage).

3.7.4 Precipitation-Streamflow Correlation Analysis

Four sets of correlation analysis were conducted and the results are presented in Table 3-3 to Table 3-5. The first set of precipitation-streamflow correlation analysis was conducted on a daily basis. The R^2 correlation coefficients are summarized in Table 3-3, and Fig. 3-6 and Fig. 3-7 show the scatter plots. In the early phases, when both watersheds maintained forest conditions, streamflow and precipitation showed little correlation—low R^2 values. Also, there was little variation of correlation between the dry and wet periods.

Table 3-3

R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of Watershed #1 (open drainage) and Watershed #2 (conventional drainage). Hurricane Allison on 6/9/2001 was excluded as an outlier

Water year	Watershed	Precipitation (>0 mm)	
		R^2	N ^a
1975-1976	#1	0.12	193
Before excluding dry periods	#2	0.07	209
1975-1976	#1	0.12	158
After excluding dry periods	#2	0.15	116
2000-2002	#1	0.03	379
Before excluding lake detention effect	#2	0.23	483
2000-2002	#1	0.01	43
After excluding lake detention effect	#2	0.37	90

^a N: the number of samples

In the later phases, the correlation remained low in Watershed #1, but increased much higher in Watershed #2. Hence, Watershed #1 stormwater management strategies seemed to be more effective than Watershed #2 in mitigating flood. In other words, the open drainage system together with The Woodlands Lake detained water more effectively than the conventional drainage system and the Bear Branch Reservoir combined. The lake and the reservoir performed a similar detention function. However, the conventional drainage system adversely contributed to the reservoir's detention effect. After The Woodlands Lake detention effect was excluded, low precipitation-

streamflow correlation was still observed in Watershed #1. The open drainage system alone suggested a viable stormwater detention solution.

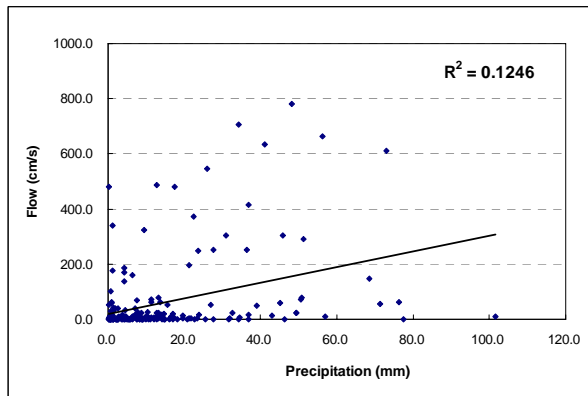


Fig. 3-6 (a)

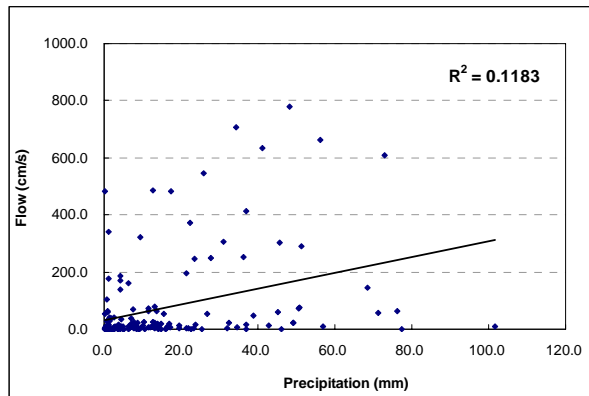


Fig. 3-6 (b)

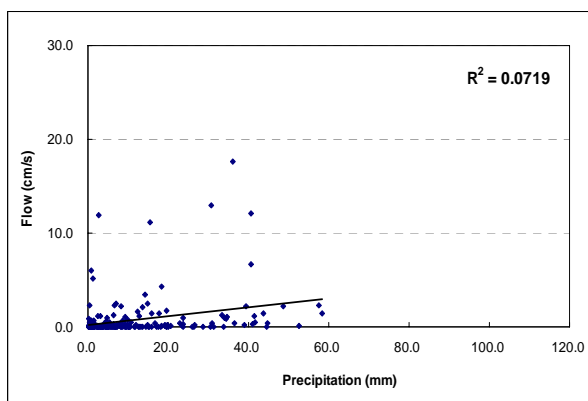


Fig. 3-6 (c)

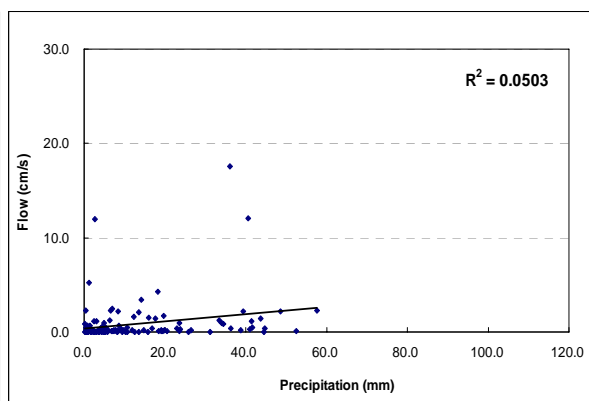


Fig. 3-6 (d)

Fig. 3-6. R^2 correlation coefficients of *precipitation* (>0 mm) and daily mean streamflow of water years 1975-1976.

- (a). Watershed #1 (open drainage), before excluding the dry periods
- (b). Watershed #1 (open drainage), after excluding the dry periods
- (c). Watershed #2 (conventional drainage), before excluding the dry periods
- (d). Watershed #2 (conventional drainage), after excluding the dry periods

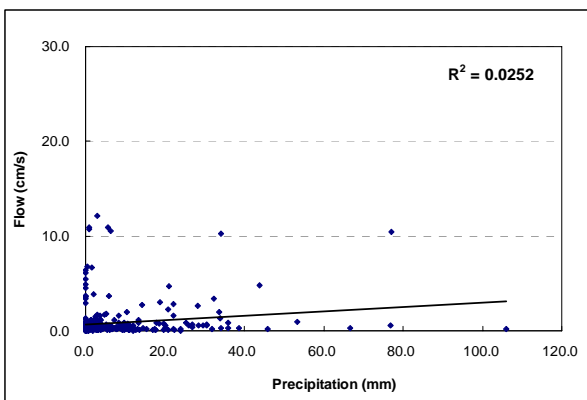


Fig. 3-7 (a)

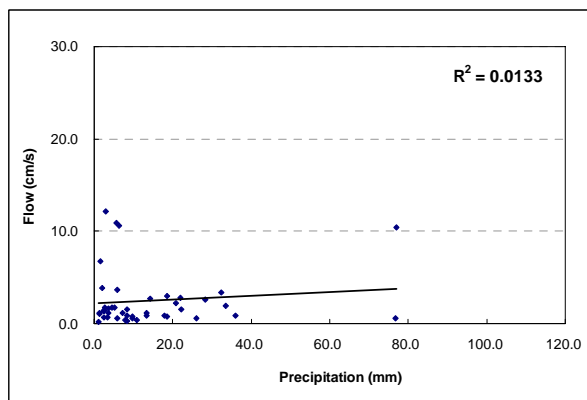


Fig. 3-7 (b)

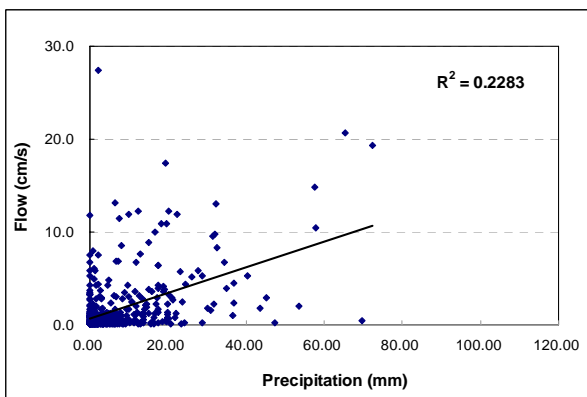


Fig. 3-7 (c)

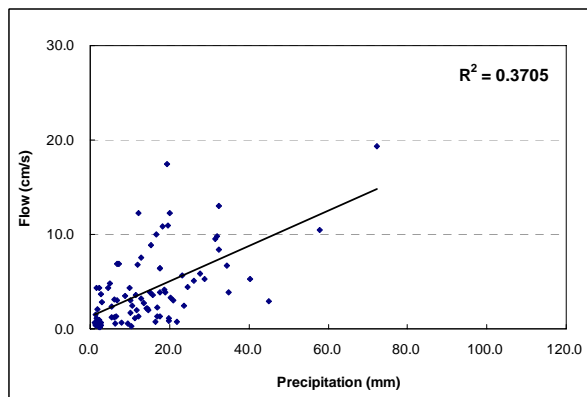


Fig. 3-7 (d)

Fig. 3-7. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of water years 2000-2002.

- (a). Watershed #1 (open drainage), before excluding the lake detention effect
- (b). Watershed #1 (open drainage), after excluding the lake detention effect
- (c). Watershed #2 (conventional drainage), before excluding the lake detention effect
- (d). Watershed #2 (conventional drainage), after excluding the lake detention effect

The second set of analysis included yearly analysis and rainfall intensity categorical analysis. R^2 correlation coefficients are listed in Table 3-4. Fig. 3-8 to Fig. 3-13 present the scatter plots. This set of analysis was only conducted for water years 2000-2002. As aforementioned, precipitation-streamflow data pairs were further divided into two categories based on precipitation values > 0 mm and > 6 mm. Similar to Table 3-3 results, Watershed #1 responded to rainfall similar to its pre-development forest condition (low R^2 's). Conversely, Watershed #2 presented high precipitation-streamflow correlations during 2000-2002 when the conventional drainage system was installed (high R^2 's).

Table 3-4

Before excluding lake/reservoir detention effect, R^2 correlation coefficients of precipitation and daily mean streamflow of Watershed #1 (open drainage) and Watershed #2 (conventional drainage). Hurricane Allison on 6/9/2001 was excluded as an outlier

Water year	Watershed	Precipitation			
		>0 mm R^2	N^a	> 6 mm R^2	N^a
2000	#1	< 0.001	98	0.004	19
	#2	0.480	134	0.447	36
2001	#1	0.001	161	< 0.001	47
	#2	0.130	191	0.058	68
2002	#1	0.176	120	0.141	31
	#2	0.296	156	0.303	53

^aN: the number of samples.

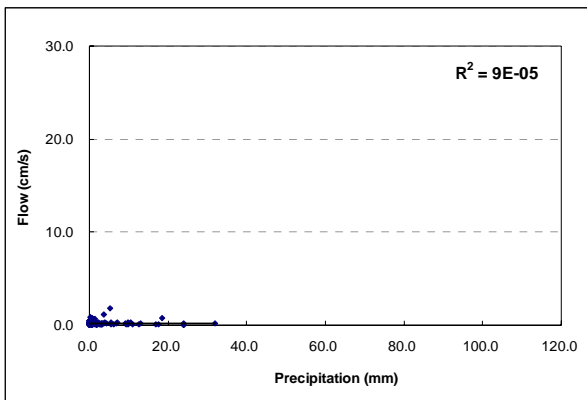


Fig. 3-8 (a)

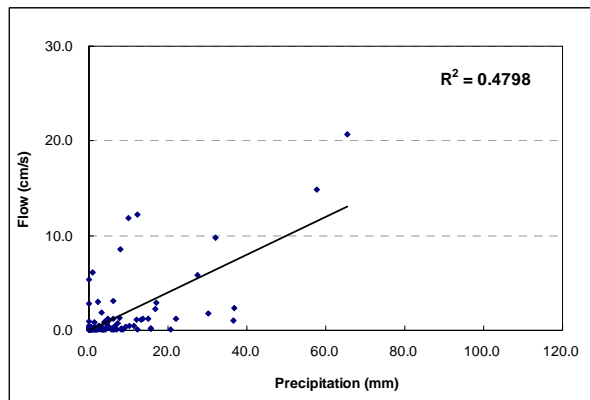


Fig. 3-8 (b)

Fig. 3-8. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of water year 2000, before excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

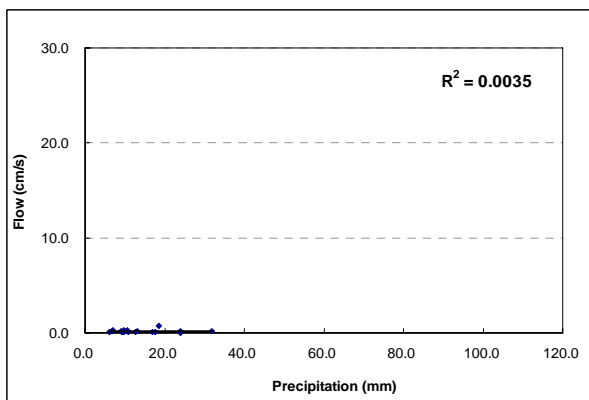


Fig. 3-9 (a)

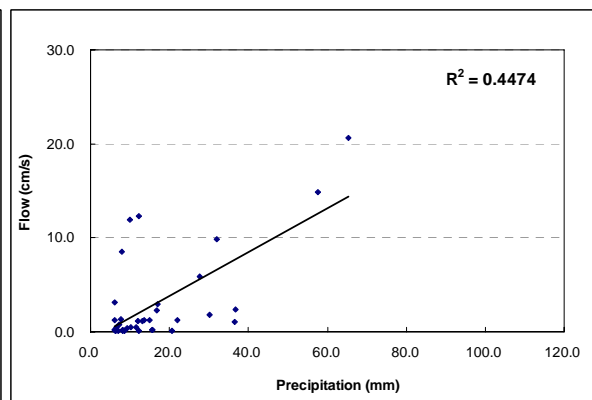


Fig. 3-9 (b)

Fig. 3-9. R^2 correlation coefficients of precipitation (>6 mm) and daily mean streamflow of water year 2000, before excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

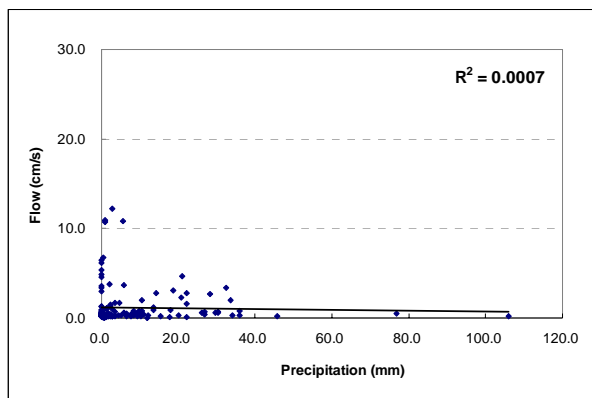


Fig. 3-10 (a)

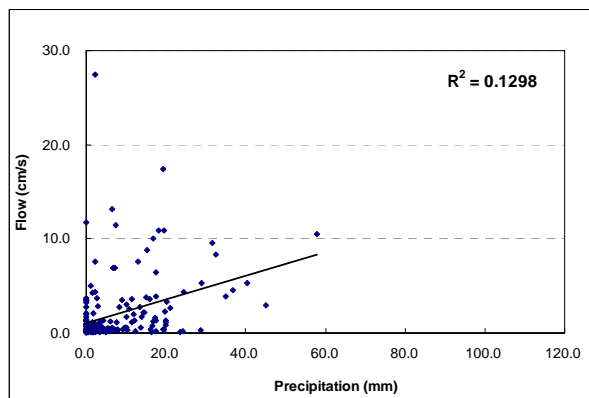


Fig. 3-10 (b)

Fig. 3-10. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of water year 2001, before excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

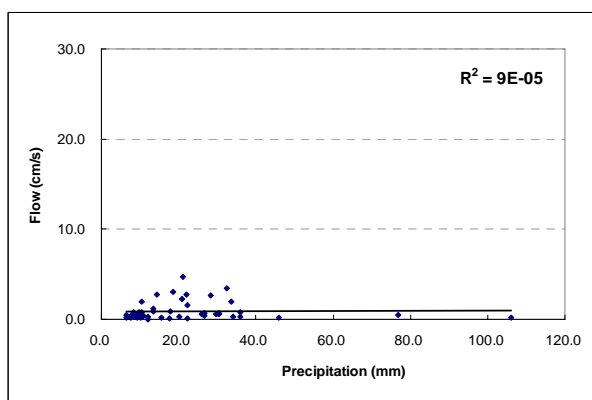


Fig. 3-11 (a)

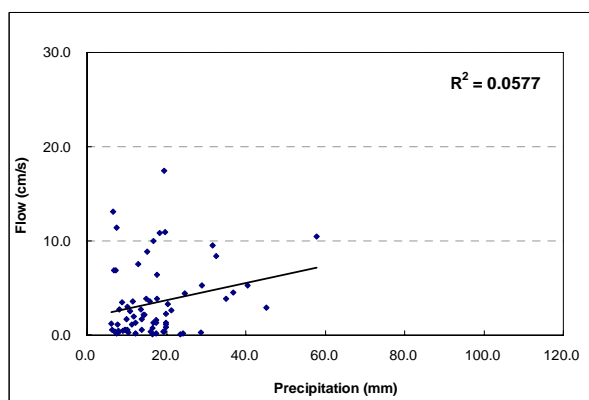


Fig. 3-11 (b)

Fig. 3-11. R^2 correlation coefficients of precipitation (>6 mm) and daily mean streamflow of water year 2001, before excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

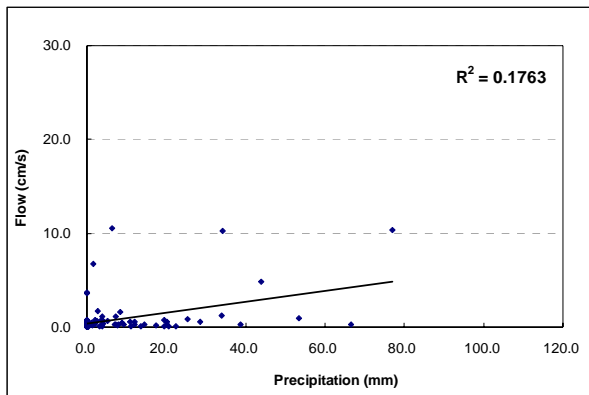


Fig. 3-12 (a)

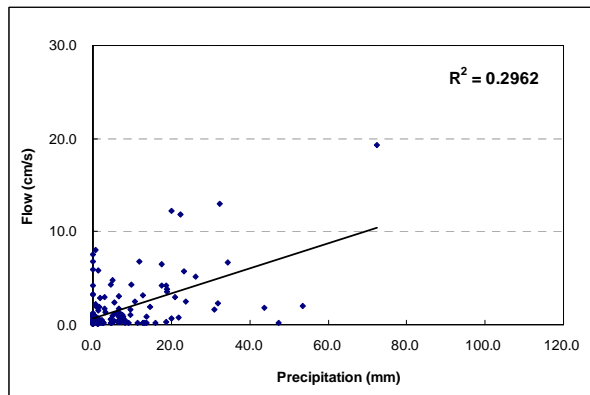


Fig. 3-12 (b)

Fig. 3-12. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of water year 2002, before excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

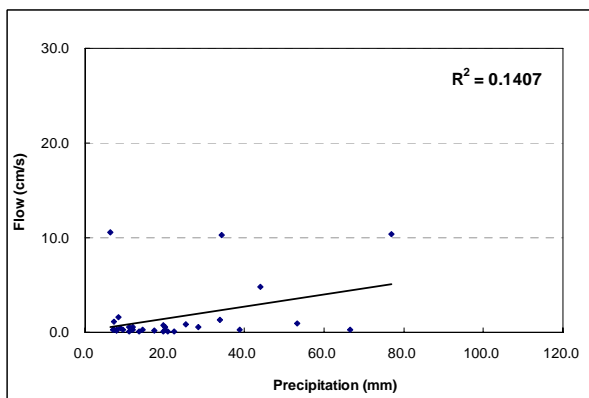


Fig. 3-13 (a)

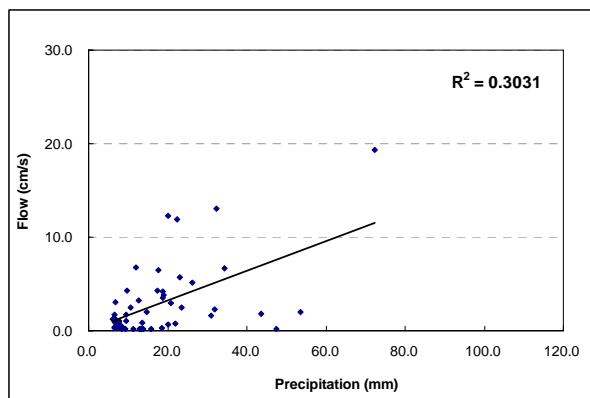


Fig. 3-13 (b)

Fig. 3-13. R^2 correlation coefficients of precipitation (>6 mm) and daily mean streamflow of water year 2002, before excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

The third set of correlation analysis was also only conducted for water years 2000-2002. R^2 correlation coefficients are listed in Table 3-5. Fig. 3-14 through Fig. 3-21 show the scatter plots. This set of analysis aimed at evaluating the flood mitigation effectiveness solely provided by different drainage systems. In this analysis, soil was saturated and the detention effects of The Woodlands Lake and the Bear Branch Reservoir was excluded.

Two models were used including the daily model and the simplified lagged model. In the daily model, Watershed #2 showed a higher precipitation-streamflow correlation than Watershed #1 for both rainfall intensities examined, indicating a situation vulnerable to flooding. In contrast, Watershed #1 showed little precipitation-streamflow correlation, suggesting that the open drainage system was effective in detaining runoff.

The simplified lagged model further demonstrated the lag-time effect, since the slope and the flow path length are similar in both watersheds. In this model, Watershed #1 showed a higher precipitation-streamflow correlation than Watershed #2. This means peak flow was less likely to occur on the same day when a large rainfall emerged in Watershed #1. In Watershed #1, yesterday's precipitation was a better predictor than today's precipitation for today's streamflow. In Watershed #2, however, yesterday's precipitation and today's streamflow showed little correlation.

This means Watershed #2 discharged runoff faster than Watershed #1 instead of detaining it. This set of analysis showed that when the detention effect of the lake/reservoir was excluded, the open drainage system presented an advantage over the conventional drainage system in mitigating flood.

Table 3-5

After excluding the lake/reservoir detention effect, R^2 model coefficients of the daily model and the simplified lagged model for Watershed #1 and Watershed #2. Hurricane Allison on 6/9/2001 was excluded as an outlier

Model	Watershed	Precipitation			
		>0 mm R^2	N^c	> 6 mm R^2	N^c
Daily model ^a					
Mean flow	#1	0.013	43	0.104	25
	#2	0.371	90	0.269	65
Max. flow	#1	0.005	43	0.029	25
	#2	0.380	90	0.302	65
Lagged model ^b					
Mean flow	#1	0.177	16	0.090	11
	#2	0.084	44	0.039	36
Max. flow	#1	0.305	16	0.226	11
	#2	0.046	44	0.020	36

^a Daily model: $Y=a+bX$. The independent variable is X: precipitation (mm). The dependant variable is Y: streamflow (m^3s^{-1}). Daily mean streamflow and daily maximum streamflow were used as the dependant variable Y.

^b Simplified lagged model: $Y = a_1 + b_1X_1$. The independent variable is X_1 : precipitation of yesterday (mm). The dependant variable is Y: streamflow (m^3s^{-1}). Daily mean streamflow and daily maximum streamflow were used as the dependant variable Y.

^c N: the number of samples.

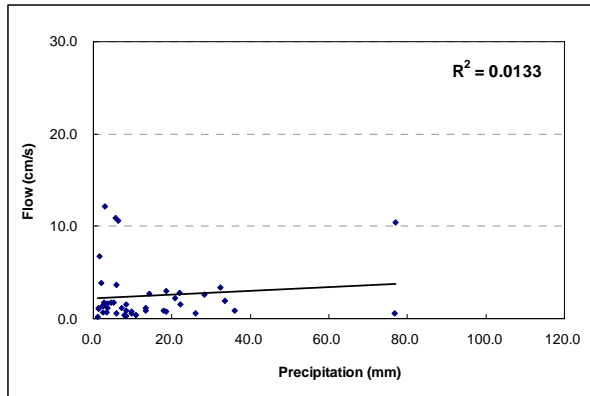


Fig. 3-14 (a)

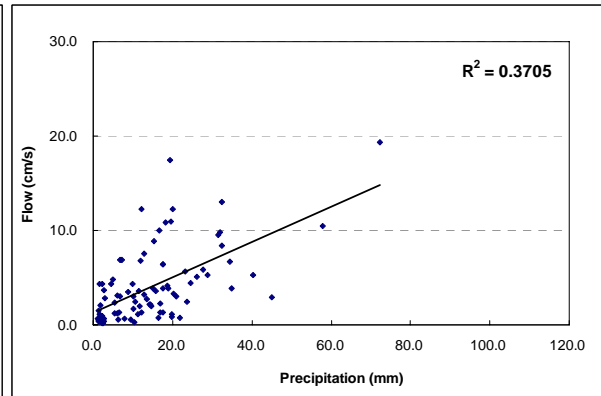


Fig. 3-14 (b)

Fig. 3-14. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow of water years 2000-2002, after excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

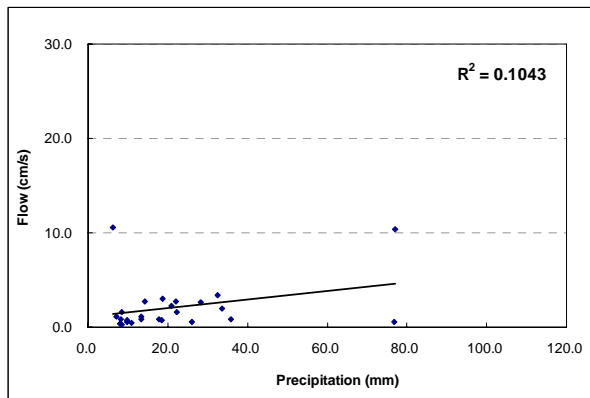


Fig. 3-15 (a)

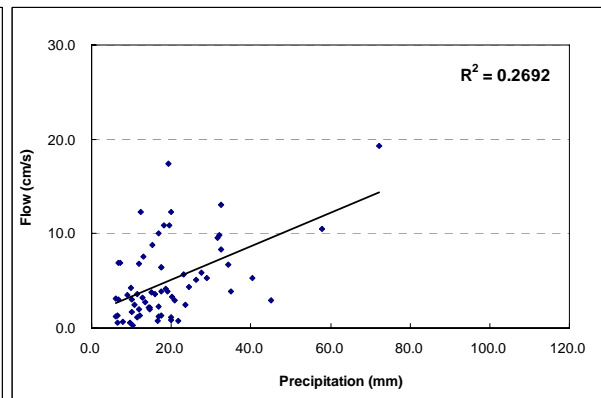


Fig. 3-15 (b)

Fig. 3-15. R^2 correlation coefficients of precipitation (>6 mm) and daily mean streamflow of water years 2000-2002, after excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

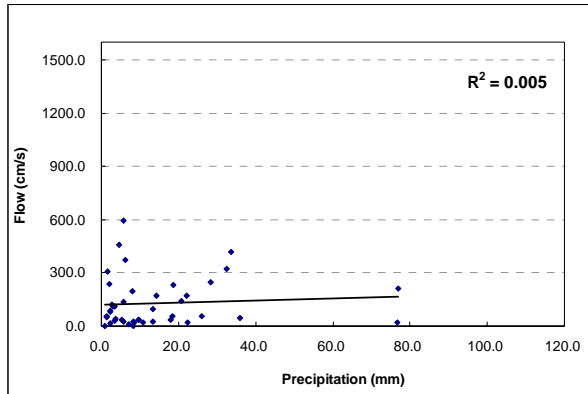


Fig. 3-16 (a)

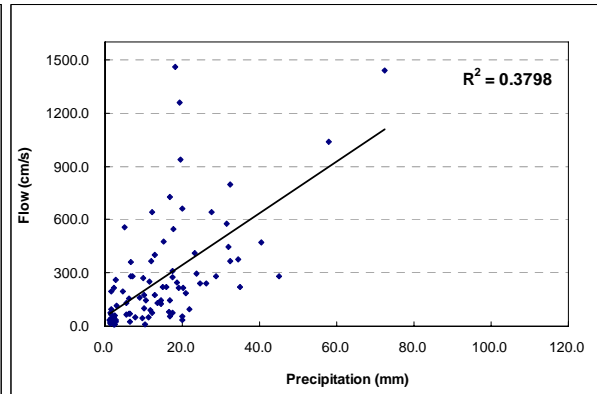


Fig. 3-16 (b)

Fig. 3-16. R^2 correlation coefficients of precipitation (>0 mm) and daily peak streamflow of water years 2000-2002, after excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

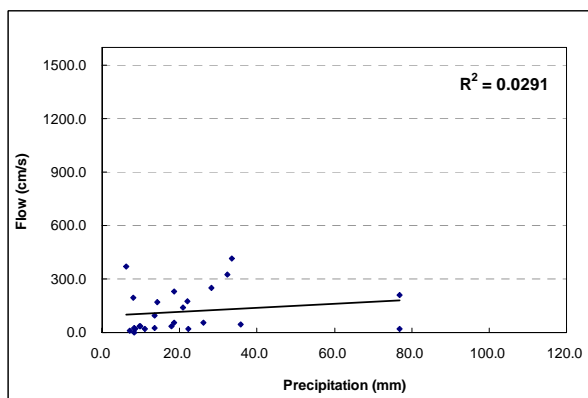


Fig. 3-17 (a)

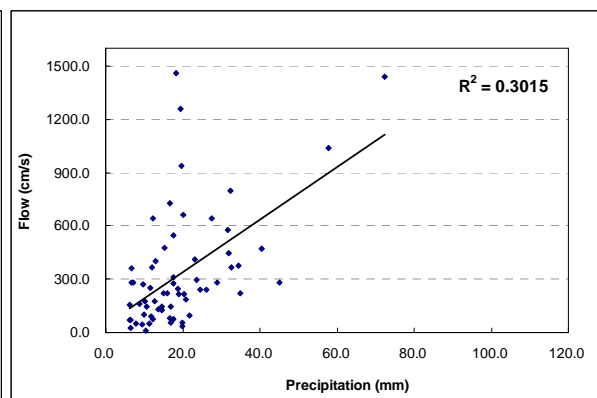


Fig. 3-17 (b)

Fig. 3-17. R^2 correlation coefficients of precipitation (>6 mm) and daily peak streamflow of water years 2000-2002, after excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

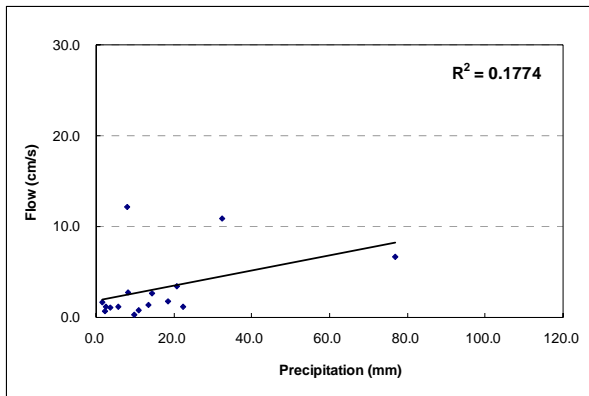


Fig. 3-18 (a)

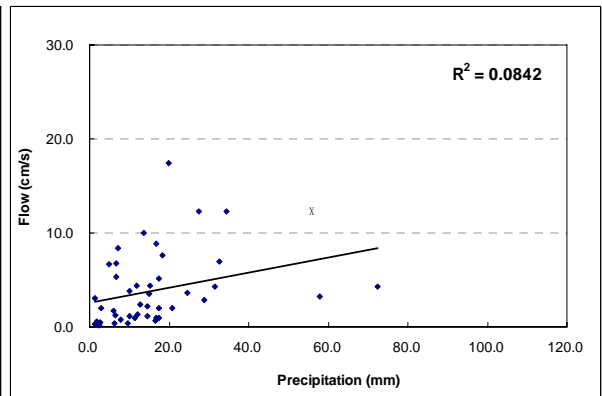


Fig. 3-18 (b)

Fig. 3-18. R^2 correlation coefficients of precipitation (>0 mm) and yesterday's mean streamflow of water years 2000-2002, after excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

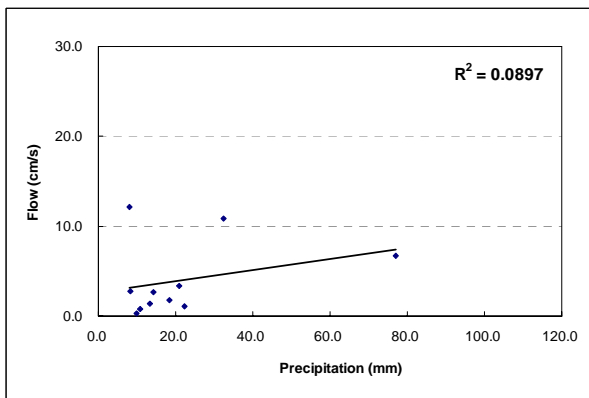


Fig. 3-19 (a)

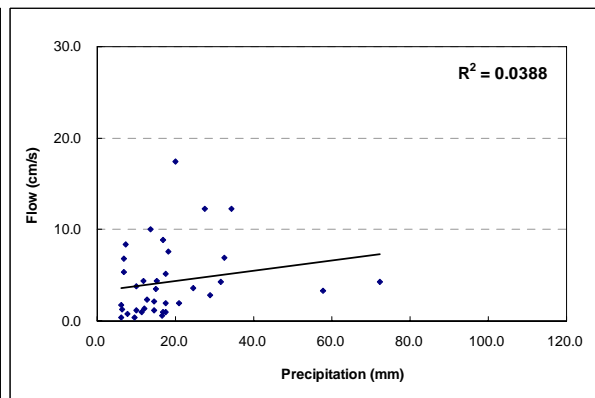


Fig. 3-19 (b)

Fig. 3-19. R^2 correlation coefficients of precipitation (>6 mm) and yesterday's mean streamflow of water years 2000-2002, after excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

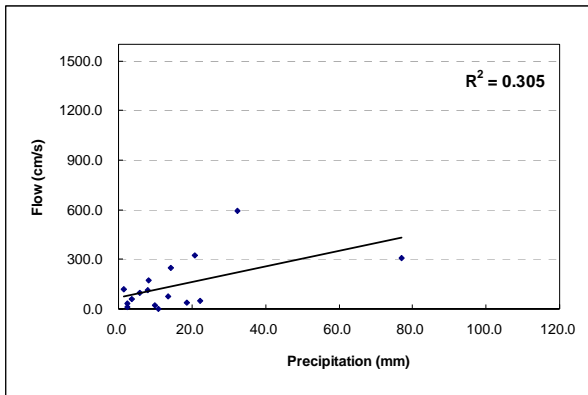


Fig. 3-20 (a)

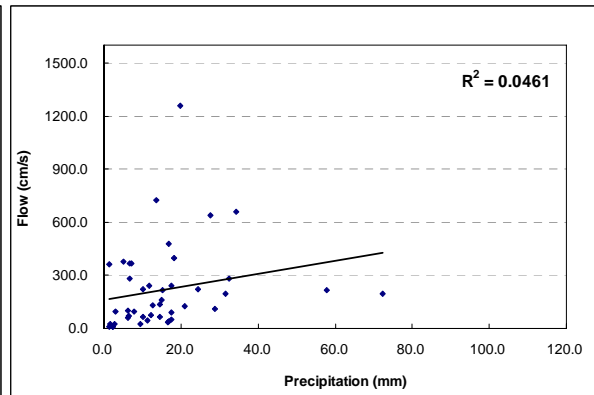


Fig. 3-20 (b)

Fig. 3-20. R^2 correlation coefficients of precipitation (>0 mm) and yesterday's peak streamflow of water years 2000-2002, after excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

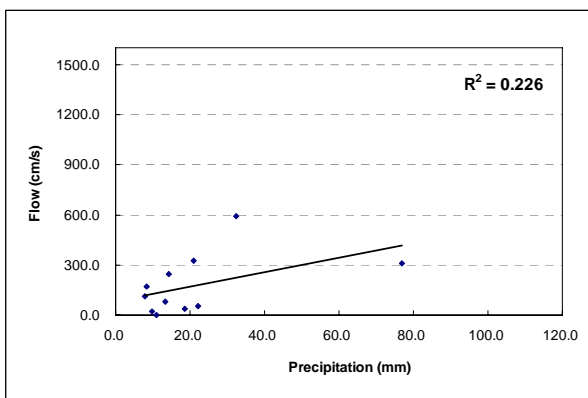


Fig. 3-21 (a)

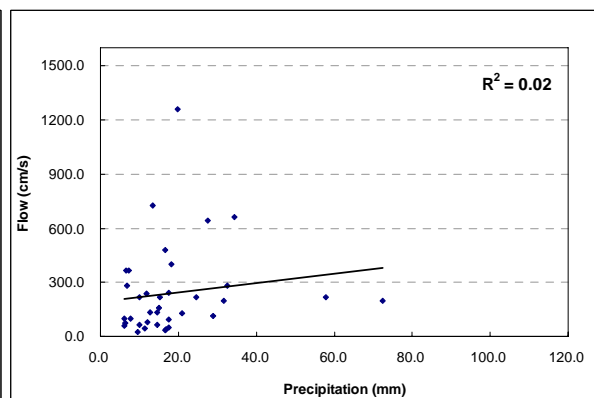


Fig. 3-21 (b)

Fig. 3-21. R^2 correlation coefficients of precipitation (>6 mm) and yesterday's peak streamflow of water years 2000-2002, after excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

The fourth set of analysis enumerated precipitation-streamflow correlation coefficients (R^2) as precipitation increases. It provided a comprehensive correlation analysis for all the precipitation-streamflow data pairs. This analysis demonstrated the incremental change of the correlation and minimized the potential bias due to the precipitation intensity thresholds specified (e.g., precipitation > 6 mm stands for large rainfall).

Fig. 3-22 and Fig. 3-23 present the scatter plots obtained from the daily model. Fig. 3-22 showed that before excluding the lake detention effect, R^2 values remained almost as low as zero in Watershed #1 regardless of the precipitation intensities. In Watershed #2, it was evident that R^2 values generally increased as precipitation increased. Fig. 3-23 showed a similar trend. That is, after excluding the lake detention effect, R^2 values remained low in Watershed #1, but the values generally increased in Watershed #2 as rainfall intensity increased. Also, comparing conditions before and after excluding the lake detention effect, the correlation became much higher in Fig. 3-23 than in Fig. 3-22, particularly during large rainfall.

Fig. 3-24 and Fig. 3-25 present the scatter plots derived from the simplified lagged model. Compared with the daily model, less obvious trends were shown. This could partly be attributed to the limited sample size after excluding the lake detention effect. However, a higher percentage of R^2 values was observed in the upper ranges of the coefficients (e.g., $R^2 > 0.2$) in Watershed #1 than Watershed #2, which still suggests that Watershed #1 was more effective in detaining runoff than Watershed #2.

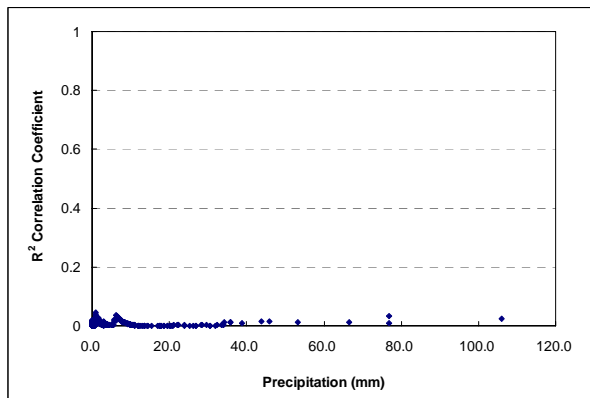


Fig. 3-22 (a)

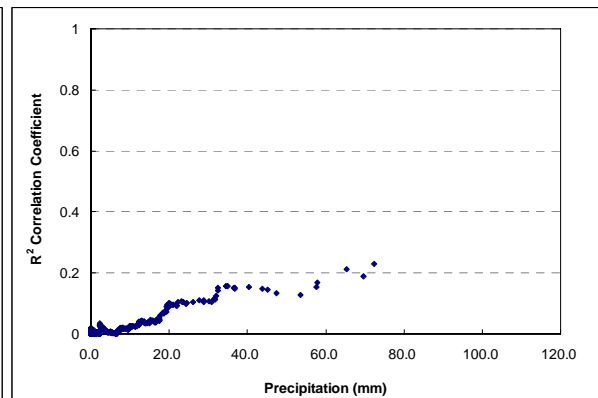


Fig. 3-22 (b)

Fig. 3-22. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow during 2000-2002, before excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

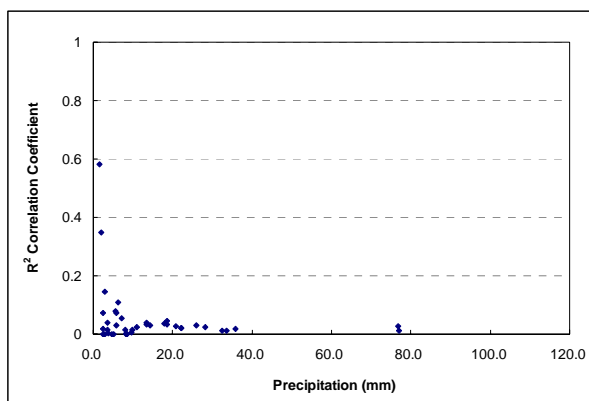


Fig. 3-23 (a)

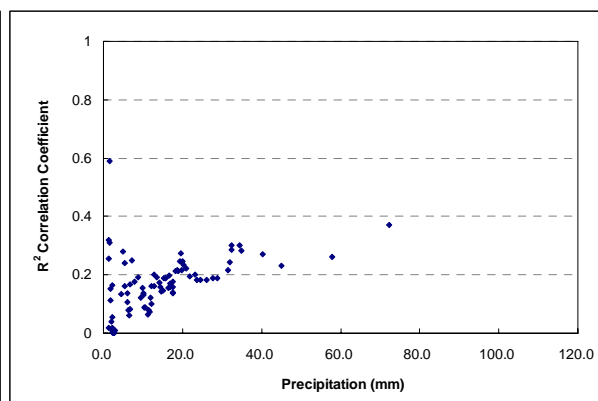


Fig. 3-23 (b)

Fig. 3- 23. R^2 correlation coefficients of precipitation (>0 mm) and daily mean streamflow during 2000-2002, after excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

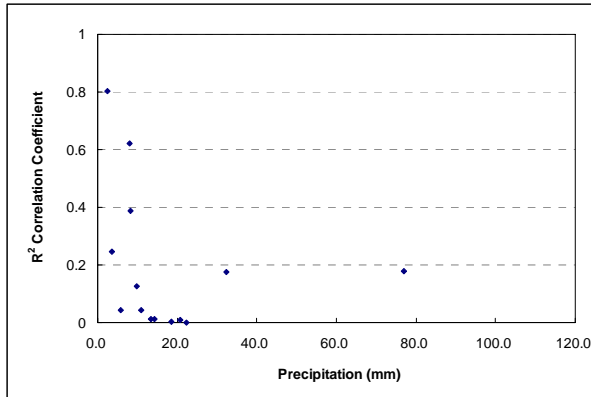


Fig. 3-24 (a)

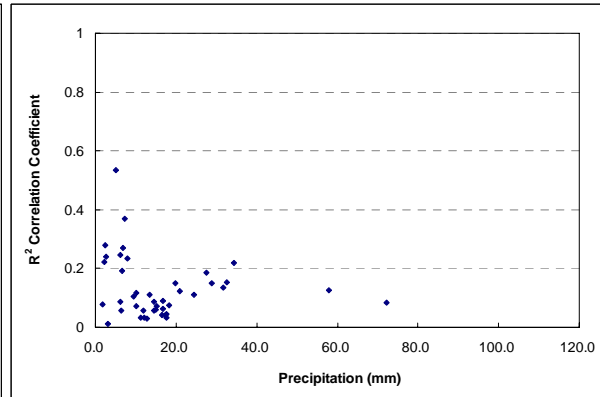


Fig. 3-24 (b)

Fig. 3-24. R^2 correlation coefficients of precipitation (>0 mm) and yesterday's mean streamflow during 2000-2002, after excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

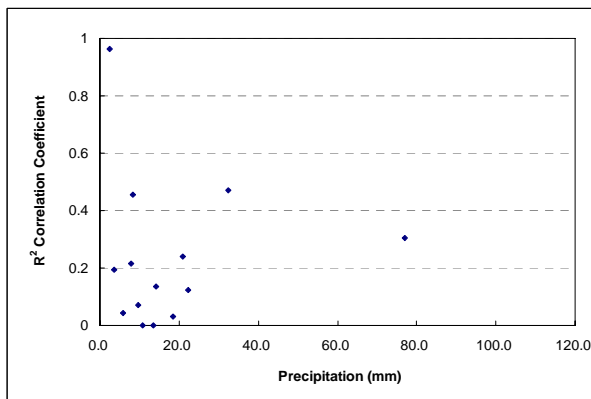


Fig. 3-25 (a)

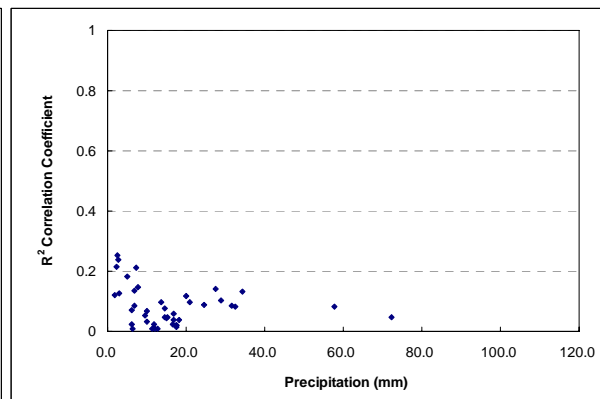


Fig. 3-25 (b)

Fig. 3- 25. R^2 correlation coefficients of precipitation (>0 mm) and yesterday's peak streamflow during 2000-2002, after excluding the lake detention effect.

(a). Watershed #1 (open drainage), (b). Watershed #2 (conventional drainage)

3.8 Discussion

The open drainage system means to detain stormwater runoff for infiltration, whereas the conventional drainage system aims at draining runoff away as fast as possible. After development, there was a 26% runoff volume increase in Watershed #1 (open drainage). However, a vaster increase, 110%, was observed in Watershed #2 (conventional drainage). Land with high permeable soils (e.g., sandy soils) accounted for 49% of Watershed #1 area and 35% of Watershed #2 area, and by 2002, developed area accounted for 32% and 21% of Watershed #1 and Watershed #2 areas respectively. Intuitively, these differences are not significant enough to engender such a vast difference in runoff (26% versus 110%). Thus the difference of runoff volume could be largely attributed to the difference between drainage designs. Compared with conventional drainage, open drainage enabled more water to be infiltrated and evaporated before discharging downstream.

Stream flow response analysis further illustrated that the conventional drainage watershed presented a high runoff increase per unit of precipitation. In 1975, both watersheds have the same streamflow response values. In 2000, however, the value of the conventional drainage watershed was *three* times of the open drainage watershed. In 2001, this ratio became *five* times. In 2002, it increased to *nine* times. Obviously the conventional drainage system has exerted much greater impacts on the natural flow regime than the open drainage watershed. Natural streams became flashy channels in the conventional drainage watershed and suggested a condition prone to flooding.

In contrast, in the open drainage watershed, streamflow peaks occurred with a longer lag time than in the conventional drainage watershed. The open drainage watershed responded to rainfall similar to its forest conditions in which streamflow did not necessarily increase when it rained. However, the conventional drainage watershed responded to rainfall in a much more sensitive manner, especially during large rainfall events. Although the Bear Branch Reservoir helped to detain runoff, the conventional watershed, but the conventional drainage system efficiently conveyed runoff to downstream and muted the reservoir's detention effect.

Moreover, the yearly correlation analysis showed that the combine effect of the open drainage system and The Woodlands Lake was consistently more effective in detaining water than the conventional drainage system together with the Bear Branch Reservoir. The Woodlands Lake (92 hectares) and the Bear Branch Reservoir (21 hectares) were designed as flood control devices (U.S. Army Corps of Engineers, 1982). After excluding the lake/reservoir detention effect, the precipitation-streamflow correlation increased more than 60% in the conventional drainage watershed. Also, in this watershed, a much higher correlation emerged, showing the positive flood mitigation function the reservoir could bring and the negative impacts on this function the conventional drainage system could cause. The Woodlands Lake shall play an important role in detaining runoff in the open drainage watershed. But even without the lake, the open drainage system still maintained a low precipitation-streamflow correlation. Moreover, the lagged model showed the elongated the lag time this drainage system could bring.

Prior to the construction of The Woodlands Lake (1985), The Woodlands survived storm in excess of the one-hundred-year levels in 1979 with little property damage (Girling and Kellett, 2005). Although not based on scientific study, it was believed that the open drainage system played a vital role in protecting The Woodlands in this significant event (Morgan and King, 1987; Galatas and Barlow, 2004). Some other storms also help explain the effectiveness of this open drainage system. On September 28, 1987, the southern Montgomery County experienced a 130 mm rain. High water and flooding was reported along Panther Creek. City of Oak Ridge North to the east of The Woodlands, and Timber Ridge subdivisions to the south of The Woodlands got flooded. In contrast, no flooding was observed in The Woodlands (NOAA, 1987). In 1994, a five-hundred-year level storm occurred in The Woodlands, with over 890 mm of rain falling within 36 hours. Again, the open drainage system successfully endured this significant event (Galatas and Barlow, 2004).

After The Woodlands took a different approach in drainage design, especially after its ownership was changed in 1997, homeowners started to complain about the flooded streets during large storms (Haut, 2006). On April 2, 2000, The Woodlands had considerable street flooding and many roads became impassable (NOAA, 2000). Again in the 2008 Hurricane Ike, a large territory of The Woodlands was flooded. The western Woodlands, developed with the conventional drainage system, was severely flooded. A number of streets and thoroughfares became impassable after the Hurricane (Madere, 2008).

This comparative study showed that the open drainage system detained runoff more effectively than the conventional drainage system. Nevertheless, the research

design could not address several confounding factors and presented some limitations. One of the limitations was the Thiessen polygon method used for estimating precipitation. The Thiessen method assumes uniform rainfall within delineated polygons. However, there were cases when flow values increased enormously while no precipitation records were shown. Because of the localized rainfall pattern in Texas, it is possible that a rain occurred within a watershed but was not captured by its nearest weather station. Due to the limitation of the Thiessen polygon method, there are inconsistency in the results of streamflow response analysis and precipitation-streamflow correlation analysis.

Another limitation was the difficulty to delineate watersheds which were ideal for the scope of study. On one hand, Watershed #1 includes a large portion of The Woodlands Town Center, a commercial area with large impervious area. The Town Center shall undermine the effectiveness of the open drainage system demonstrated in the results. On the other hand, Watershed #1 contains less than one third of the Village of Grogan's Mill, the only one that strictly used McHarg's open drainage design. In short, the effectiveness of the open drainage system was not fully illustrated due to the limitations of the research design.

3.9 Conclusions

This study provides evidence that the open drainage system is more effective than the conventional drainage system in mitigating flood. The open drainage system

generates less runoff volume and increases the lag time to reach peak flow. Therefore, the open drainage system presents a viable alternative to the conventional drainage system in community development, particularly in the Houston area, where annual hurricane generates intense precipitation in short durations. Although clay soil will hinder stormwater infiltration, the open drainage swale provides greater storage than the curb-and-gutter drainage system. Moreover, the meandering shape of swales elongates the time for runoff to reach streams.

McHarg's open drainage design mimicked the natural hydrologic cycle so that urban developments' impacts on the watershed could be minimized. This innovation, however, did not come easily. Cultural preferences sometimes transcend the ecological benefits in the design decision making process. Such has been the case in The Woodlands when the open drainage system was changed to the conventional drainage solutions because of its lack of popularity among homeowners (Kutchin, 1998; Gatalas and Barlow, 2004). The well-protected pine forest may give homeowners and visitors an impression that this town is developed in harmony with nature, but the less visible ecological values which open drainage could bring, is often beyond what the general public could comprehend. It takes time for the general public to value and appreciate the ecological design innovations.

This study also suggests that large detention facilities, such as The Woodlands Lake or the Bear Branch Reservoir, present an effective stormwater management strategy. In addition, the synergic effect of the open drainage system and The Woodlands Lake is an even better strategy. Also, the location of the open drainage channels and the detention facilities become important planning and design issues. For example, McHarg

placed the open drainage channels where high permeable soils were available for stormwater infiltration (WMRT, 1973b, 1974). The Woodlands Lake and the Bear Branch Reservoir were also strategically located to collect runoff from different drainage zones (WMRT, 1974; U.S. Army Corps of Engineers, 1982; Bedient et al., 1985). Future study shall investigate how watersheds response during single intense storms, an important issue related to flooding.

CHAPTER IV

MCHARG'S WOODLANDS AFTER 35 YEARS: WHAT WORKS AND WHAT DOES NOT

4.1 Synopsis

The Woodlands, Texas, is one of the most publicized new towns created under Ian McHarg's ecohydrological planning approach. George Mitchell, a self-made oil and real estate businessman and an environmental-conscious developer, launched this project in the 1970s. During 1972 to 1996, McHarg's planning approach was followed when Mitchell presided over the development. The Woodlands survived storms in excess of one-hundred-year levels in 1979 and 1994 with little property damage. After 1997, McHarg's planning approach was largely abandoned when Mitchell sold The Woodlands ownership. Accelerated pace of construction occurred and more pronounced environmental impacts emerged—The Woodlands was flooded in 2000 and again in the 2008 Hurricane Ike. However, for the past three decades, little effort has been invested in documenting the evolution of the ecohydrological plans. This study reviews McHarg's original planning concepts, demonstrates the design implementations and unveils the obstacles to continue McHarg's innovations. Lessons learned from The Woodlands' development have implications for today's community planning and design practices.

4.2 Introduction

Since the late 1960s, suburban development in the United States has been criticized for “ecological damage, excessive energy use, high infrastructure cost, and loss of open space” (Forsyth, 2002, p. 387). The environmental crisis during the 1960s and 1970s called for a better understanding of the relationship between human beings and the ecosystem. A series of national policies such as the National Environmental Policy Act (NEPA, 1969) and the Clean Water Act (1972) were enacted to curb the environmental degradation.

The Woodlands, Texas, was considered as an alternative to suburban sprawl. This 27,000-acre new town development was created under Ian McHarg’s ecohydrological planning approach. “It is the best example of ecologically based new town planning in the United States during the 1970s” (McHarg, 1996, p.325). Maintaining the site hydrologic balance and the aesthetic values of the forest became the development focuses (WMRT, 1973c; 1974). McHarg’s ecohydrological plans were in essence based on the carrying capacity of the land. His Landscape Suitability Analysis (LSA) approach integrated environmental and other principle factors to determine where and how much development a land was able to support (Neuman, 2000). Plans for The Woodlands demonstrated the applicability McHarg’s approach from the regional planning scale to the site-level design scale (WMRT, 1973b).

Started in 1972, The Woodlands is 48 kilometers north of Houston. Currently there are eight residential villages in The Woodlands, seven of them are located in Montgomery County, and the eighth village is located in Harris County. The

Woodlands' 2006 population exceeded 83,000 (The Woodlands Development Company, 2007). It is expected that The Woodlands will be substantially completed around 2015 (Galatas and Barlow, 2004).

Several monographs and journal articles have mentioned McHarg's planning concepts, yet less effort has been invested in introducing how his concepts were implemented and adjusted overtime. Documenting The Woodlands project evolution holds significant implications and will shed light for today's community planning and design practices.

4.3 Background and Past Studies

The Woodlands project was initiated by George Mitchell, son of Greek immigrants and a self-made oil and real estate businessman. Mitchell graduated from Texas A&M University, majoring in petroleum engineering with an additional emphasis in geology. He established his own firm, Mitchell Energy & Development Corporation and made his fortune in the 1950s' booming oil industry (Malone, 1985; Morgan and King, 1987). Mitchell's vision to develop this new town did not come accidentally. As he traveled around the nation, he was concerned about the economic and environmental problems associated with urban development. Mitchells' strong social responsibilities motivated him to help cure the American urban illness: urban blight, high crime, jobless, and white-collars' exodus to suburbia. He has been trying to find an alternative growth

model, in lieu of the suburban sprawl model used post World War II (Lance, 1982; Forsyth, 2005).

The most important step in developing The Woodlands, Mitchell recalled, was to hire the landscape architect and environmental planner—Ian McHarg (Morgan and King, 1987; Galatas and Barlow, 2004). McHarg was known as a pioneer of ecological planning and design. McHarg established the benchmark status for The Woodlands development using the ecohydrological planning approach. Stormwater management was the major emphasis in his plans (WMRT, 1973b). The Woodlands survived storms exceeding one-hundred-year levels in 1979 and 1994 with little property damage (Girling and Kellett, 2005). However, flooding was reported in The Woodlands in 2000 and more recently in 2008 Hurricane Ike (NOAA, 2000; Madere, 2008).

Past studies have documented The Woodlands development history. An early article by McHarg and Sutton (1975) features The Woodlands ecohydrological planning concept in the *Landscape Architecture Magazine*. The first monograph, by Morgan and King (1987), documents early history of the development (1964-1983). The second monograph is written by Galatas and Barlow (2004), further adding the following 10 years. Ann Forsyth (2002, 2005) compares The Woodlands with another two large-scale master planned communities: Irvine, California and Columbia, Maryland. The study shows that these new town projects would still benefit the current practice in the social and environmental aspects. Kim's (2005) doctoral dissertation compares The Woodlands with north Houston development. The study concludes that stringent development guidelines lead to more ecologically structured environment than development planned according to the conventional ordinances.

McHarg's ecohydrological plans were mentioned in almost all the previous studies on The Woodlands. However, after 35 years of The Woodlands' inception, very few studies have been conducted to examine the effectiveness of McHarg's ecohydrological planning approach. In addition, this planning approach has not been replicated at this regional scale until today. McHarg suggested in his 1975 article that a post occupancy evaluation of the project will increase the collective knowledge of the profession (McHarg and Sutton, 1975). This study reviews the original planning concepts, how they were implemented, and how they were changed. In addition, this study provides insights into how to promote the ecohydrological planning approach in the current planning and design practices.

4.4 Project Precedents

George Mitchell had invited a number of teams to preside The Woodlands planning and design. The first plan was proposed by a Houston architect Karl Kamrath in 1966 (Malone, 1985) (Fig. 4-1). Kamrath proposed a 20,000-acre site a population of 50,000, but the plan was a traditional subdivision. The second plan was prepared by Cerf Ross, another Houston architect, in 1969. Ross proposed a 15,000-acre community, which has four residential villages surrounding a business complex (Malone, 1985).

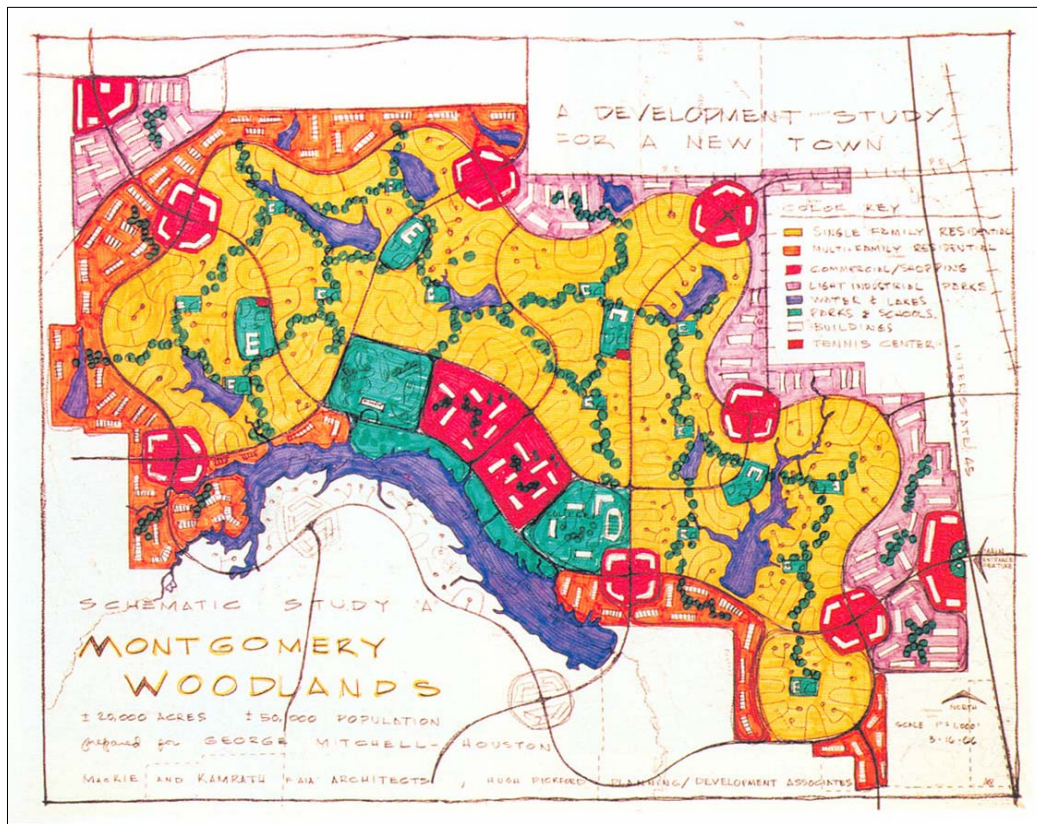


Fig. 4-1. The first master plan of The Woodlands, by architect Karl Kamrath, 1966.

Source: Malone, 1985, p.10.

Originally, Mitchell thought about seeking private financial sources for this project. However, based on these early plans, Mitchell realized the tremendous financial requirements. Right at that time, the Urban and New Community Development Act was passed, under which the Department of Housing and Urban Development (HUD) can provide loan guarantees at maximum of \$50 million to new town developers (Malone, 1985; Morgan and King, 1987).

Encouraged by the HUD financial support, Mitchell decided to submit a proposal in February 1970 and Ross' plan was included. The pre-application proposal was

approved on June 17, 1970, but Mitchell was invited to assemble a more competent team for a more polished application (Malone, 1985). Robert Hartsfield, director of planning and design in Mitchell's firm at that time, once studied under world-renowned environmentalist Ian McHarg at University of Pennsylvania. Hartsfield recommended McHarg to Mitchell by suggesting him to read McHarg's *Design with Nature* (McHarg, 1969). Mitchell was thoroughly impressed by this book and decided to hire McHarg's team, Wallace, McHarg, Roberts and Todd (WMRT) (Malone, 1985; Morgan and King, 1987).

Subsequently, Mitchell assembled a strong team including some of the top names in the nation. McHarg's team, WMRT, was in charge of environmental planning. This team included Narendra Juneja, Jonathan Sutton, Mokun Lokhande, Anne Spirn, Colin Franklin, Leslie Sauer, and James Veltman. William L. Pereira Associates of Los Angeles was to prepare land use planning. Gladstone Associates of Washington, DC was to provide an economic analysis. Richard P. Browne Associates of Columbia, Maryland, was the engineering consultant. Another team from University of Texas School of Public Health was to help with institutional and social planning for The Woodlands (Malone, 1985; Morgan and King, 1987).

Mitchell resubmitted a formal proposal to HUD on March 31, 1971, and the master plan on August 10. Revised plans were submitted on November 23, 1971, and received HUD approval. The Woodlands became the only project which received the maximum loan at \$50 million among the 13 new towns funded by HUD (Morgan and King, 1987; Kutchin, 1998).

In the early period of the project, McHarg spent a great deal of time discussing with Mitchell about his innovative ideas. Mitchell, McHarg and Browne travelled all over the world to visit new towns and cities, such as Tivoli gardens of Denmark, sidewalk cafes in Paris, old piazzas in Rome, Georgetown in Washington, DC, and the Riverwalk in San Antonio. The Woodlands' planning and design was informed by those successful examples (Malone, 1985).

4.5 Ecohydrological Plan

The lush pine forest made The Woodlands' site attractive for development. However, designers faced stringent site conditions. About one third of the site lies within the 100-year floodplains of the three creeks on site, making developable land limited. In addition, the poorly-drained soils and extremely flat site cause drainage problems (WMRT, 1973a, 1973b). Local people say that you cannot tell where the water is going unless you know the wind direction. The annual precipitation of the Houston area is around 840 mm. However, coastal hurricanes usually cause widespread flooding by generating intense rainfall in single events. Conventional developments had occurred sporadically in the pine forest before The Woodlands started. Concrete ditches were constructed to facilitate runoff. This solution, however, will lower the ground water table and lead trees to death. The lowered ground water table may also sink the high-rise buildings in downtown Houston (McHarg, 1996).

McHarg's main goal was to preserve the pine forest after development. The plans put emphasis on maintaining the site hydrologic balance in order to keep the ground water table. A series of design strategies were developed. The major strategies included (1) preserving permeable soils for stormwater infiltration, (2) maintaining forest preserve, and (3) using open surface drainage instead of curb-and-gutter drainage. Early environmental planning was based on MchHarg's strategies, according to which the choice of land-use largely depended on the soil permeability (McHarg and Sutton, 1975; MchHarg, 1996). Additionally, a landscape clearance index specified the site's maximum clearance based on the soil and vegetation conditions. Finally, an open drainage system was designed for Phase I development—Village of Grogan's Mill. MchHarg was in favor of using grassed swales to collect runoff. Conventional curb-and-gutter drainage was banned (WMRT, 1973c; MchHarg, 1996).

At first, Mitchell and his staff were skeptical about the open drainage solution, because they did not believe that landscape architects and planners know hydrology better than engineers. Mitchell asked Espey Associates, his engineering consultants, to process MchHarg's solution on their computers. Later, Espey people reported with embarrassment that MchHarg's open drainage solution worked. They also confirmed the enormous saving this solution could provide. Conventional drainage would cost \$18.7 million, whereas open drainage would be \$4.2 million, a \$14 million saving for Phase I alone.

MchHarg's team WMRT delivered a preliminary report on the ecohydrological planning on March 14, 1971 (WMRT, 1971; Morgan and King, 1987). Following that, Jonathan Sutton with WMRT continued to create four more polished reports in 1973 and

1974 for HUD approval. These reports included ecological inventory, land planning, site planning, and a final ecological plan (WMRT, 1973a, b, c; 1974). Not limited to environmental data, the WMRT studies moved forward as the contemporary rational planning method (Forsyth, 2005). The first report, the ecological inventory, described the existing natural phenomena, including geology, ground water hydrology, surface hydrology, limnology, pedology, plant ecology, wildlife, climatology, and landscape interacting processes (WMRT, 1973a). The other three reports included ecological data interpretations, assessment of landscape tolerance, design synthesis, guidelines, and plans for Phase I development (WMRT, 1973a, b, c; 1974).

4.5.1 Preserve Permeable Soils

Permeable soils were preserved for stormwater infiltration, according to McHarg's plans. If comparing the design synthesis map (Fig. 4-2) and the land-use map (Fig. 4-3), it is evident that a large percentage of development was placed on soils with low infiltration capacities. At the site-level design, design guidelines also required preserving land with high permeable soils as open space and building on land with less capability to soak runoff (Fig. 4-4).

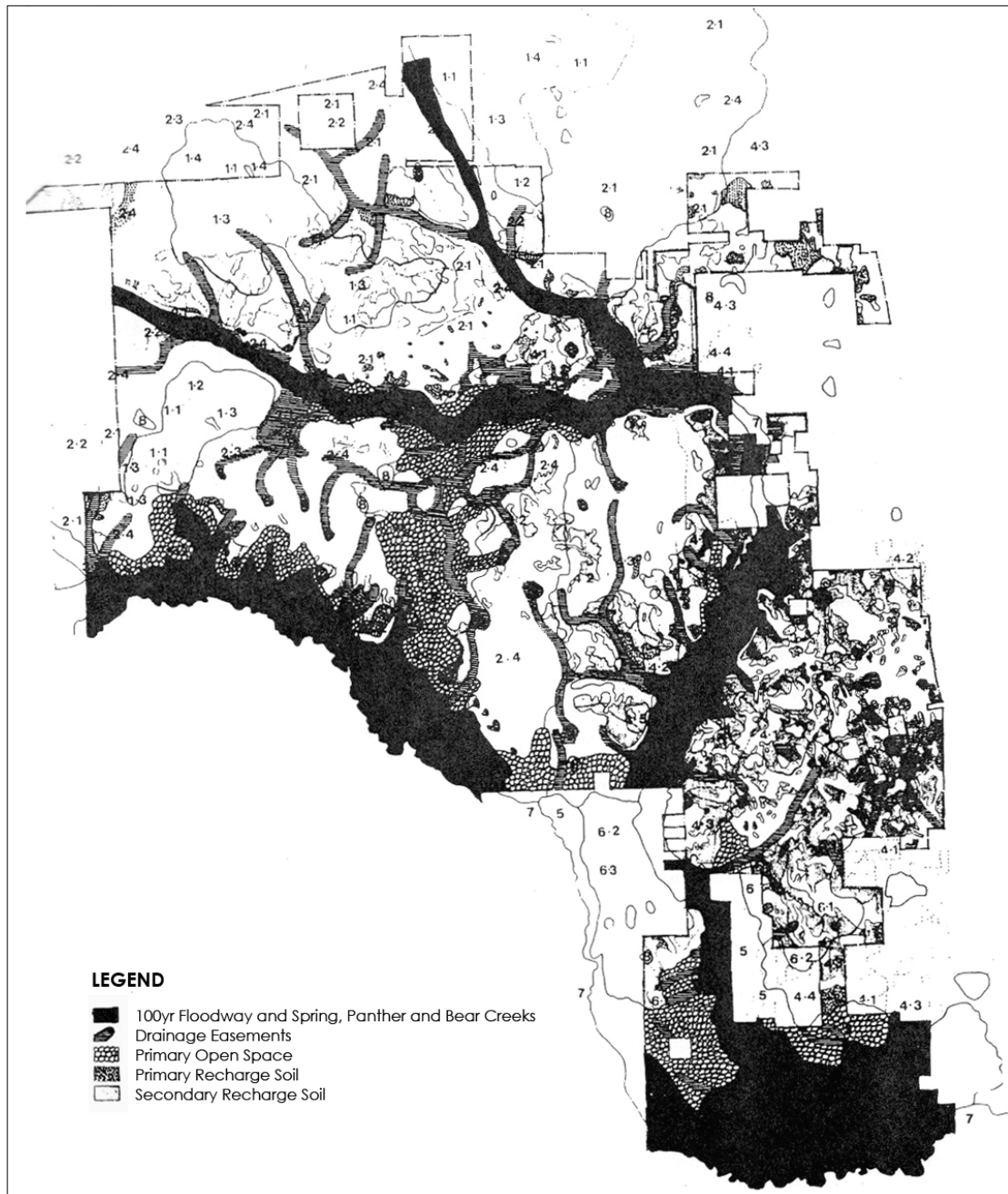


Fig. 4-2. Design Synthesis. The dark areas are flood plains of the three major creeks.

Map shows primary open space and recharge soils. Source: WMRT, 1974, p.35.

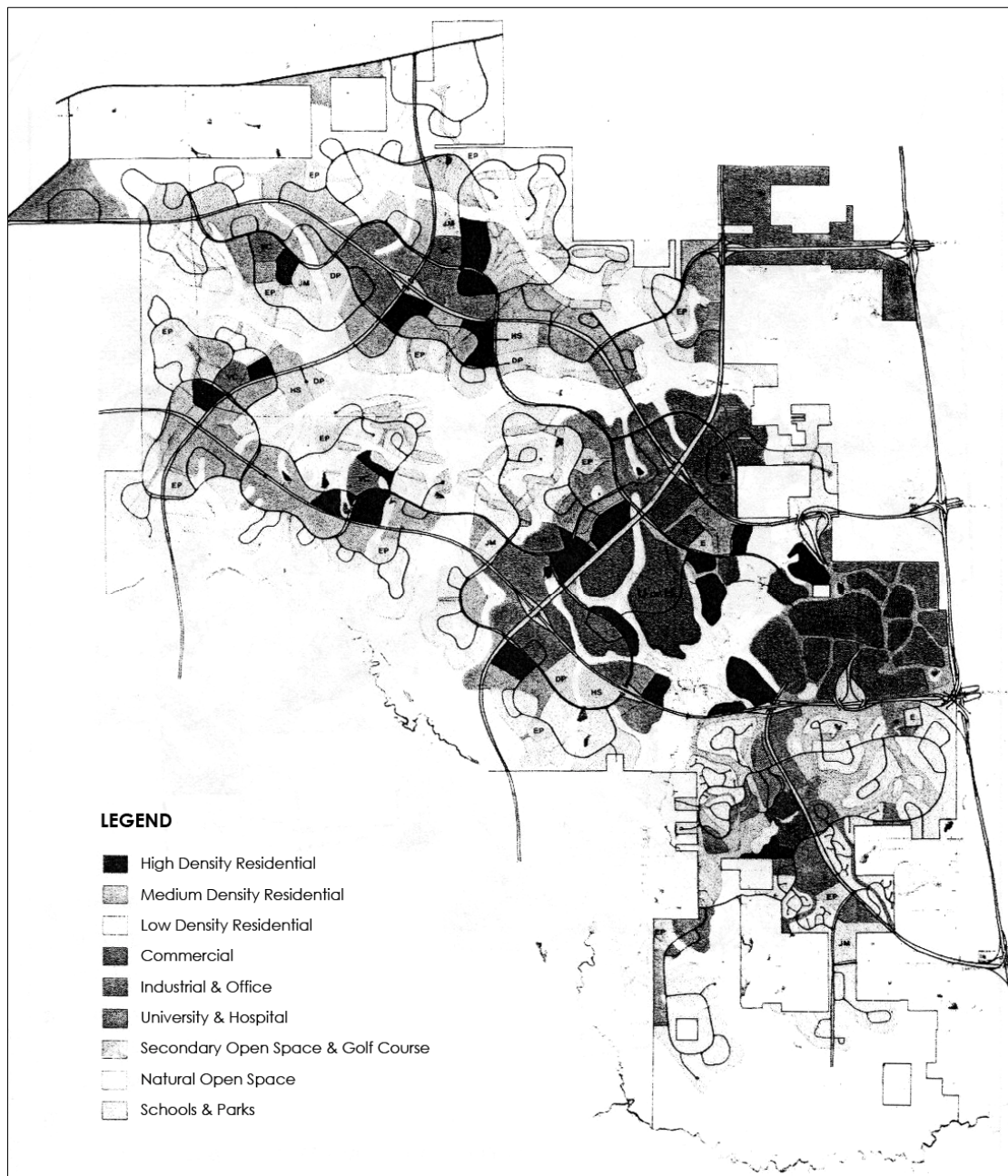


Fig. 4-3. Land-use Plan. The darker the area, the higher the building density is. High density land-uses were proposed relatively near the roads and to avoid prime recharge soils. Source: WMRT, 1974, p.41.

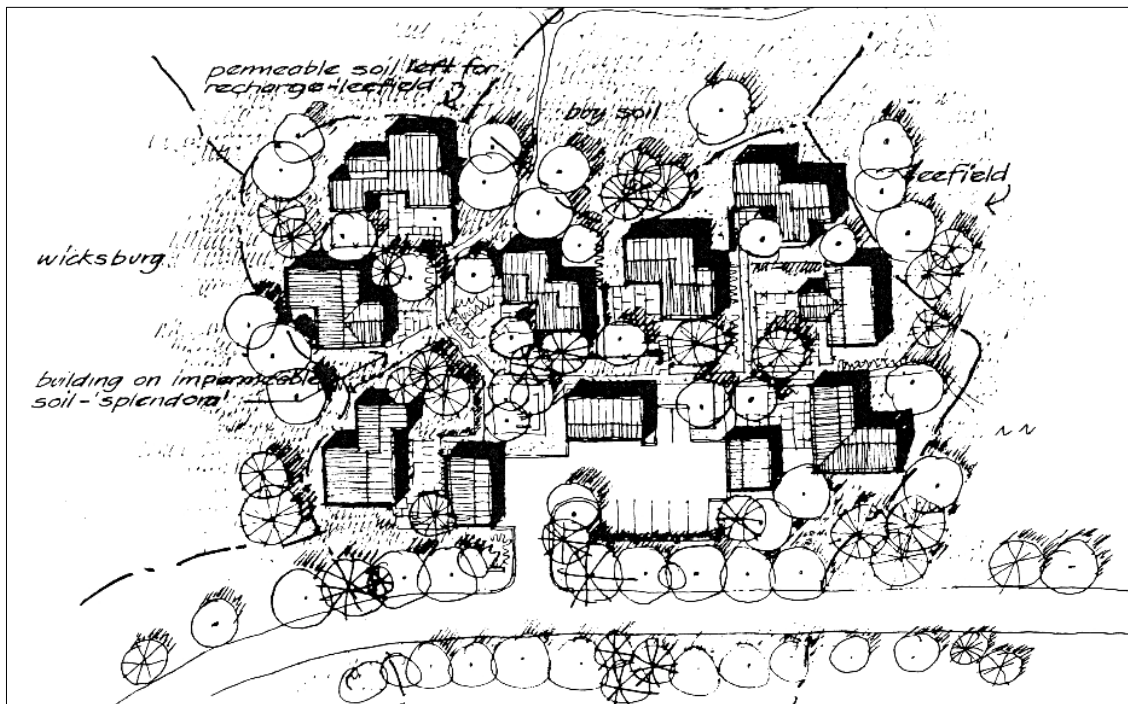
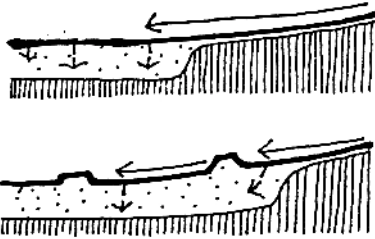
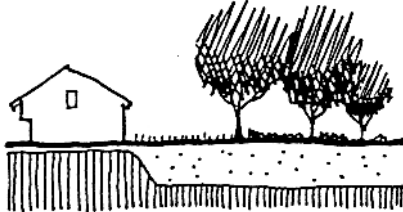
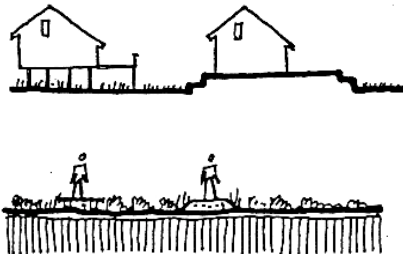


Fig. 4-4. Site-level design guidelines. Housing cluster and grouped parking conformed to the boundaries of soils with low infiltration capacities. Source: WMRT, 1974, p.72.

McHarg's team also developed guidelines for site with different soil compositions (Table 4-1, Fig. 4-5). It is ideal to build low-density housing types (e.g., estate lots) where the parcels are large, leaving plenty of exposed soil to allow runoff to infiltrate. On less permeable soils, high-density housing types and commercial land-uses become good choices. This is because adding high-coverage land-uses onto less permeable soils will not substantially increase stormwater runoff (WMRT, 1973b; Galatas and Barlow, 2004).

Table 4-1

Site planning guidelines for soils

Objective 1	Use recharge capacities of suitable soils to enhance a natural drainage system and even out base flow of streams
<p>Adaptations</p> <ul style="list-style-type: none"> • Direct runoff over permeable soils with excess storage capacity • Use roads, berms, and checkdams in swales to impound runoff by blocking flow over permeable soils 	
Objective 2	Minimize coverage of permeable soils
<p>Adaptations</p> <ul style="list-style-type: none"> • Locate structures on impermeable soils. • Locate backyards and intensively used recreation areas on permeable soils. 	
Objective 3	Houses and outdoor activity areas should be located to be as dry as possible
<p>Adaptations</p> <ul style="list-style-type: none"> • Buildings and patios should be constructed on raised foundations or fill • Pedestrian paths should be raised or on fill if located on impermeable soils 	

Note: Table adapted from WMRT, 1973b, p.11.

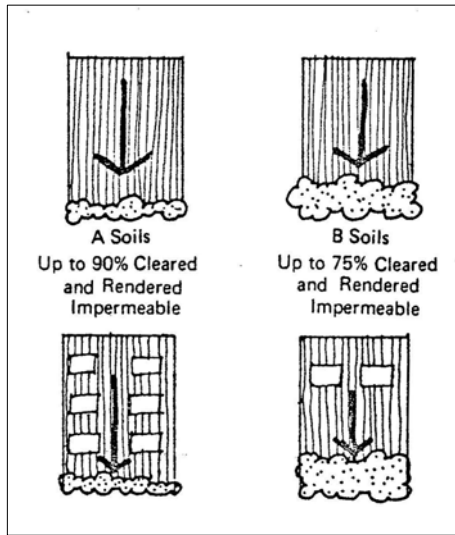


Fig. 4-5 (a)

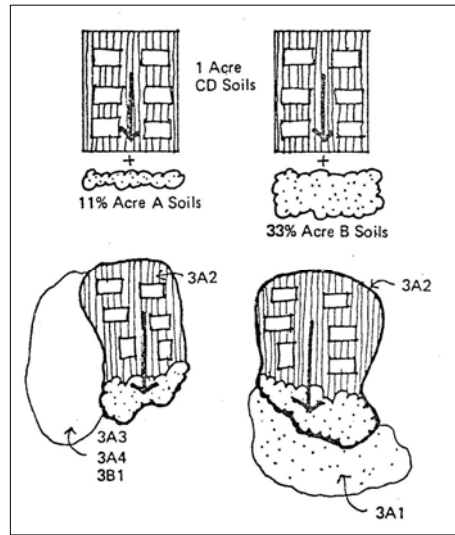


Fig. 4-5 (b)

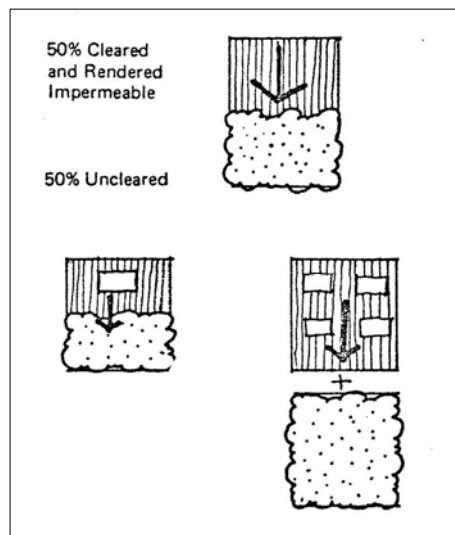


Fig. 4-5 (c)

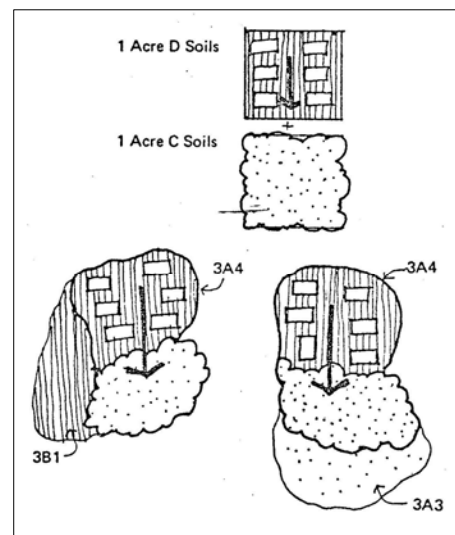


Fig. 4-5 (d)

Fig. 4-5. Development guidelines for site with different soil conditions.

Map adapted from WMRT, 1973b, p.30-33.

- (a). A soils² may be cleared up to 90% and still achieve local recharge of the 2.5 mm (1”) storm. B soils may be cleared up to 75% and still achieve local recharge of the 2.5 mm (1”) storm. Areas used for recharge should remain wooded.
- (b). A soils: for every cleared area to be drained, an area equal to 11% of uncleared LA or EU soils must be provided to accomplish recharge of the 2.5 mm (1”) storm.
B soils: for every cleared area to be drained, an area equal to 33% of uncleared BOH or AL soils must be provided to accomplish recharge of the 2.5 mm (1”) storm.
- (c). C soils may be cleared up to 50% and still achieve local recharge of the 2.5 mm (1”) storm. Areas used for recharge should remain wooded.
- (d). For every area of D soils to be drained an equal area of uncleared C soils is required to accomplish recharge of the 2.5 mm (1”) storm. After sufficient C soils have been allotted to accomplish recharge of runoff from D soils, the remaining C soils may be developed according to guidelines and suitability outlined in Fig. 4-5 (c).

WMRT reports also demonstrated the zero-runoff concept in today’s stormwater management (Ferguson, 1995; Echols, 2008). For Phase I development, sub-watershed’s storage capacity was calculated (Fig. 4-6). Positive numbers indicated the sub-watershed’s storage volume, and negative numbers showed expected runoff volume from the same sub-watershed. Design strategies were needed so that the watershed as a whole produced no excessive runoff (WMRT, 1973c).

² U.S. Department of Agriculture (USDA, 2002) defines soil group according to hydrologic properties. There are four hydrologic soil groups: A, B, C and D. A soils are sandy and loamy sand soils; B soils are sandy loam and loam soils; C soils are silt loam and sandy clay loam soils; D soils are clay loam, silty clay loam and clay soils. A soils have the highest infiltration capacities. B and C soils have the modest infiltration capacities. D soils have the least infiltration capacities.

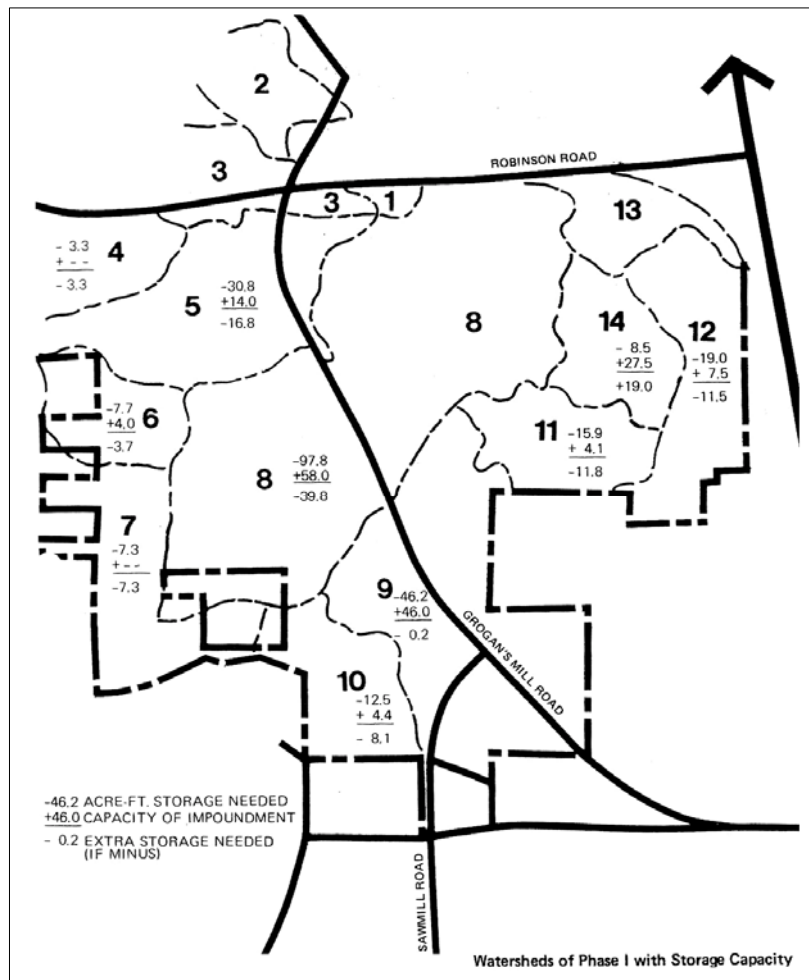


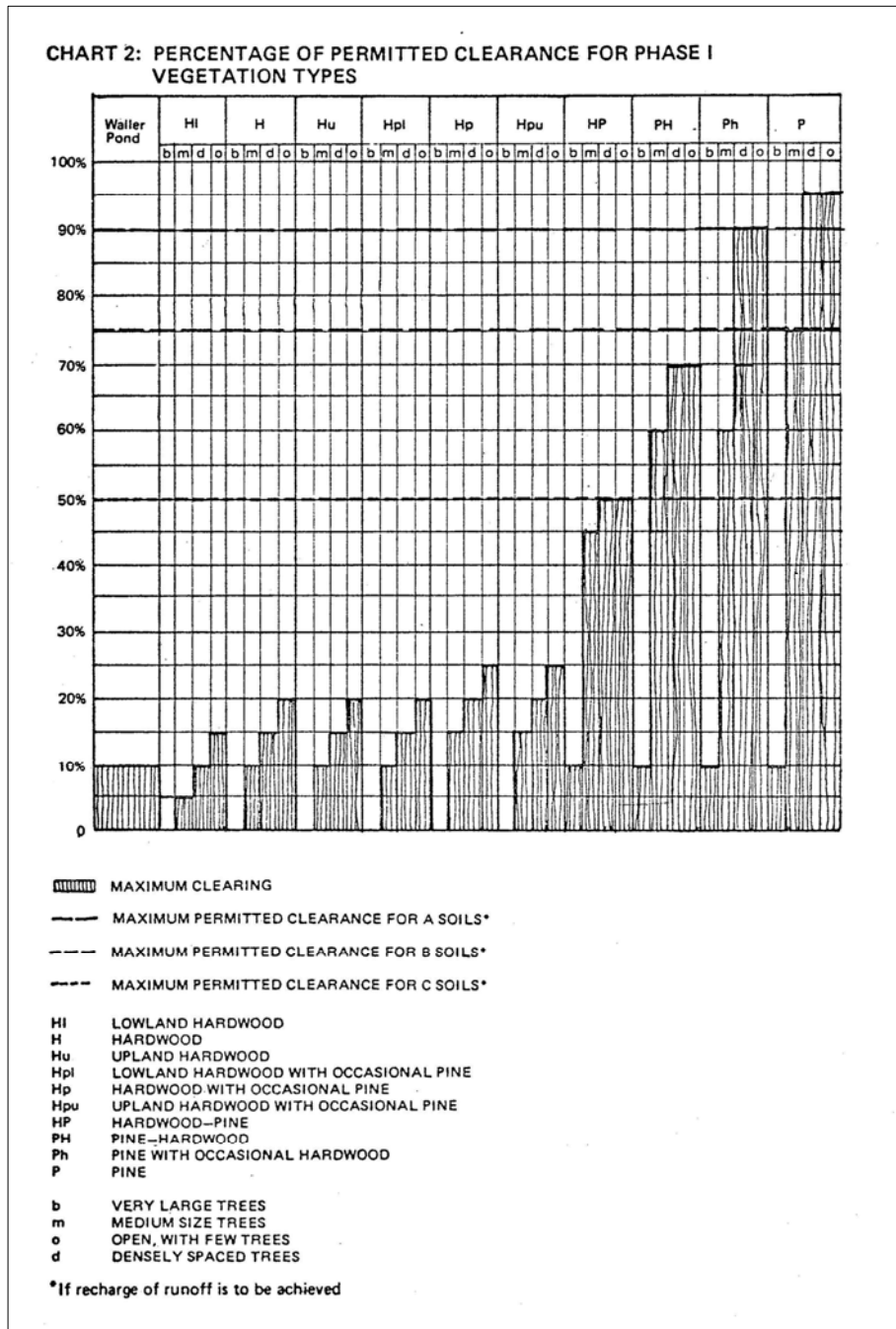
Fig. 4- 6. Watershed storage capacity of Phase I development. Source: WMRT, 1973c, p.9.

4.5.2 Preserve Forest Environment

There were two major components to protect the forest. One component was to preserve trees and understory along the major streets. Buildings were then usually hidden by the tree mask. Hence, visitors and homeowners were given the distinct

impression that the forest environment was protected after development. The other component was to maintain the natural forest within a parcel of land. Minimum disturbance was allowed to the site, according to the landscape clearance index developed by the WMRT studies (Kutchin, 1998; Galatas and Barlow, 2004). As a result, there were trees preserved in parking lots, near buildings, in community parks, etc.

The landscape clearance index was provided for different vegetation and soil combinations (Fig. 4-7), and this index was enforced on each parcel (WMRT, 1973b, p.39). During the planning process, this index allowed vegetation and soil environmental factors to be evaluated in order to rank the site constraints and opportunities. For example, a pine forest with the highest recharge soils (e.g., sandy soils) could be cleared up to 90%, regardless of the types of vegetation. If the forest has medium-high recharge soils (e.g., sandy loam and loam soils) and medium-sized trees, the allowed clearance is then reduced to 75%, and the recharge area should remain forest. Some advanced technologies at that time were used including analyzing infrared images to identify different tree species. Landscapes of high ecological values were targeted for preservation in the WMRT studies (WMRT, 1973b).



4.5.3 Open Surface Drainage

McHarg's open surface drainage system meant to save \$14 million construction costs compared with the conventional curb-and-gutter drainage system (McHarg, 1996). During heavy rainfall, the roadside open drainage channel prevents runoff from staying on the pavement better than the curb-and-gutter street in order to maintain traffic flow. This is because in an open drainage condition, the built-up street allows proper drainage whereas in a curb-and-gutter condition the street is depressed to collect runoff (Galatas and Barlow, 2004).

Another benefit of the open drainage system was that substantial excavation was not required. Therefore existing vegetation in drainage easements along swales and creeks and within development areas was preserved. This system also provided significant double savings: the expenses of the artificial drainage system and the expenses of replanting trees (WMRT, 1974).

4.6 Design Implementations

McHarg's concepts were strictly followed in the first village (Village of Grogan's Mill) and part of the second village (Village of Panther Creek), but were adjusted to meet the homeowners' preferences in the later rest villages. A significant setback from the original plans took place in 1985, although the spirit of the "ecological plan" remained in the community mission statement (Girling and Helphand, 1994). The year 1997 witnessed a further adjustment to the plans when George Mitchell sold The

Woodlands ownership to Crescent Real Estate Equities and Morgan Stanley Real Estate Fund II, after which development sped up (Clay, 1998; Galatas and Barlow, 2004).

Despite the negative deviations, a green infrastructure was established based on McHarg's plans (Gause et al., 2002). This green infrastructure includes maintenance of 100-year flood plains of the three creeks on site, drainage easements, greenways and more than 100 parks (108 by year 2007) (The Woodlands Development Corporation, 2007).

According to Roger Galatas, former president of The Woodlands Corporation, changes to the original plans were because subsequent events made them unrealistic or unprofitable. The low market acceptance of the open drainage system and complaints about the largely invisible commercial development from outside led the corporation to shift the development emphasis from ecohydrological planning to economic viability (Galatas and Barlow, 2004). Design implementations of key components in McHarg's plans are reviewed in the following text.

4.6.1 Preserve Permeable Soils

Chapter II results show that McHarg's concept of preserving permeable soils was followed before 1997 but ceased to be adhered after 1997. In 1972, development started in Village of Grogan's Mill. During the period of 1972 to 1996 (Phase I & II), soils with high permeability (e.g., sandy soils) were given a high priority of protection. In Phase III, when The Woodlands ownership was sold in 1997, the development pattern did not present such a consideration.

The ownership change presented a dichotomy. Moreover, some members from the early planning team maintained a different opinion from McHarg's (Kutchin, 1998; Galatas and Barlow, 2004). For example, Mitchell's senior in-house urban planner, Robert Heineman, thought that McHarg's approach exhibits some limitations. Heineman was hired by Robert Hartsfield in the summer of 1972 when Hartsfield was head of the planning department. Heineman received architecture degree from Rice University and later a master degree in urban design from Harvard. He has been involved in The Woodlands development since 1972 (Kutchin, 1998).

Heineman noted that majority of the soils, rather than those in the floodplains, had only moderate recharge capacities (2.5-5 cm). The soil conditions were not as varied as the proposed plan indicated (Galatas and Barlow, 2004). McHarg's plans also used depressing areas in backyards to soak runoff. The development team members recalled that they received many complaints when it rained. Residents complained about the stagnant water in their backyards and their kids playing in the mud. To make things worse, water in the backyards and in the open drainage channels bred mosquitoes (Morgan and King, 1987; Galatas and Barlow, 2004).

4.6.2 Preserve Forest Environment

The greatest success following the original McHarg's plan, according to Heineman, was to preserve 25 percent of the natural forest environmental after development (Galatas and Barlow, 2004). By 2007, 5,410 acres of land was preserved

from development. This area included 1,620 acres forest preserve, 2,100 acres open space and 1,690 acres golf courses (The Woodlands Development Company, 2007).

Although natural preserve was a novel idea in the Houston market in the 1970s, the development team experienced adverse reactions. The challenge was not to save trees since most homeowners loved trees. One of the challenges was that land available for development decreased. Members from the real estate division were concerned about the project economic feasibility (Kutchin, 1998; Galatas and Barlow, 2004). As a result, the original land availability analysis was revised by Land Design Research (LDR), a Columbia based land consultant firm (Forsyth, 2005).

Another challenge was that people expected manicured landscaping which required clearing the understory. The accepted norm of commercial development was that commercial buildings were meant to be seen rather than hidden. The Woodlands Corporation put a covenant in the deed restriction, requiring the understory remain intact. This covenant, however, was not always followed. Because of the stringent covenants on landscape preservation, some tensions were also created between the Corporation and the commercial developers (Kutchin, 1998; Galatas and Barlow, 2004).

When Mitchell's company was leading the development, a total of 9,603 acres of land was developed. After The Woodlands ownership was sold in 1997, much accelerated development pace occurred (Haut, 2006). During the following five-year period (1996-2001), an additional 3,556 acres of land was developed (Table 4-2). Until 2001, The Woodlands has converted a total of 4,084 acres of its original undeveloped forest preserve into residential, commercial and various other types of development. Over the same five-year period, The Woodlands gained a substantial amount of

grassland, bare land and developed open space (NOAA), and developing the previously forest preserve was expected to continue through 2011 (Haunt, 2006). According to Roger Galatas, former president of The Woodlands Corporation, construction of The Woodlands will be completed probably 10 years earlier than the original anticipated year by Mitchell, year 2025 (Galatas and Barlow, 2004).

Table 4-2

Land-use change in The Woodlands from 1996 to 2001

Land Cover in The Woodlands, TX (27,000 acres)					
CLASS	1996 acres	%	2001 acres	%	% change
Developed	9,603	35.6	13,159	48.7	13.2
Developed Open Space	908	3.4	1214	4.5	1.1
Cultivated/Pasture	667	2.5	588	2.2	-0.3
Grassland	356	1.3	733	2.7	1.4
Forest	11,041	40.9	6,957	25.8	-15.1
Scrub/Shrub	1,028	3.8	740	2.7	-1.1
Wetlands	5,836	21.6	5,642	20.9	-0.7
Bare Land	95	0.4	400	1.5	1.1
Water	330	1.2	336	1.2	0.0

Source: NOAA coastal change analysis program, adapted from (Haut, 2006).

4.6.3 Open Surface Drainage

Open surface drainage—the third key method in McHarg’s plans—was also revised after development of the first two villages. Open surface drainage was installed along residential streets within neighborhoods in Grogan’s Mill and part of Panther Creek villages. After that, curb-and-gutter drainage substituted the open drainage within

the neighborhoods. However, open drainage was still maintained along collector streets, major thoroughfares and from residential neighborhoods to major streams (Kutchin, 1998; Great Planned Communities, 2001).

The open drainage was not used mainly because of its negative visual impacts to the homeowners (Kutchin, 1998; Galatas and Barlow, 2004). For example, for a typical neighborhood with a lot of 50-feet wide, there were 20-feet culvert with two head-walls and a 30-feet open-surface drainage channel. Another maintenance problem also emerged when some homeowners used the channels as trash dumpsters. Market survey showed that most homeowners preferred the more visually appealing curb-and-gutter drainage compared with the rustic open drainage (Kutchin, 1998; Gause et al., 2001; Galatas and Barlow, 2004). For the same reason, the rustic natural vegetation along the floodplains of the major streams were also cleared and regularly mowed to increase visibility (Haut, 2006).

Chapter III results show that the conventional drainage watershed generated greater runoff volume than the open drainage watershed, despite the fact that both watersheds have similar development and natural conditions (e.g., soil, topography elevation, etc.). In addition, if comparing the early and later phases of development, a noteworthy increase of runoff occurred in the conventional drainage watershed, whereas the increase was less obvious in the open drainage watershed. Hence, the difference of runoff volume could be largely attributed to the difference between the drainage designs. The open drainage system detained large amount of water for infiltration and evapotranspiration. Conversely, the conventional drainage system facilitated runoff and created greater amount of runoff.

4.7 Flooding: After Ecological Plans Were Abandoned

Deviations from McHarg's ecohydrological plans have caused greater impacts on the forest environment, though the consequences may not be observed after decades. Unfortunately, the encroached green infrastructure failed to protect The Woodlands in a 2000 storm and 2008 Hurricane Ike. In Hurricane Ike, flooding was reported especially in neighborhoods developed after 1997 (NOAA, 2000; Madere, 2008). In 2000, NOAA reported flooding in The Woodlands after a 5 mm (2-inch) storm. Again in 2008 Hurricane Ike, a large territory of The Woodlands was flooded. The western Woodlands, which was developed after 1997, was particularly hard-hit by the Hurricane. *Houston Chronicle* reported substantial structure and tree damage. An initially drive-by assessment of properties by The Woodlands Fire Department showed 400 to 450 homes suffering substantial damage (Madere, 2008).

Additionally, flooding was observed in neighborhoods and parks, especially in those developed after 1997. Seventeen parks were closed because of the hurricane damage, fifteen of which were located in villages built by the new developers. Some streets and thoroughfares got flooded and impassable after the Hurricane, including parts of Lake Woodlands Drive and Research Forest Drive in north Woodlands. Grogan's Point, an infill development built after 1997 and in the first village, was also flooded (Madere, 2008). When the open drainage was changed to curb-and-gutter drainage, residents began to complain about the flooded streets in heavy rainfall. In contrast, residents in Grogan's Mill and Panther Creek villages seldom have such complaints (Galatas and Barlow, 2004; Haunt, 2006).

4.8 Barriers to Implement Ecohydrological Plans

4.8.1 Homeowner (Demand)

From the homeowner side, the major challenge was the low acceptance of McHarg's planning and design strategies. The innovative strategies do not *look good* to the average homeowners (Fig. 4-8). The open drainage design is perhaps still less acceptable today. The rustic appearance of natural vegetation, the unkempt understory in particular, runs contrary to American's favor of manicured lawn (Nauseer, 1995).

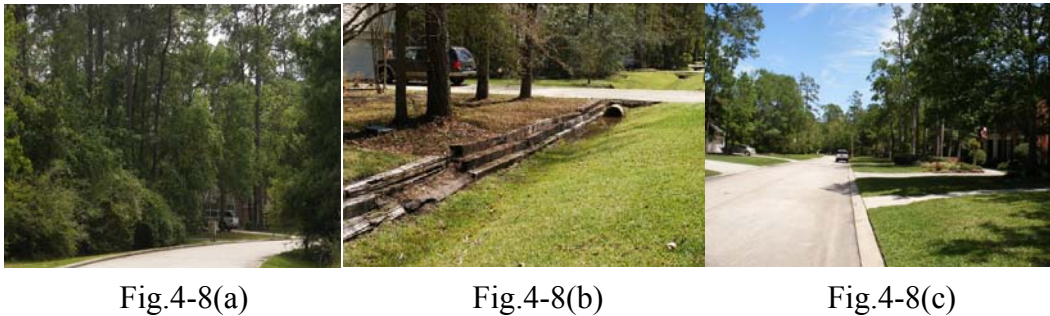


Fig. 4-8. Different drainage solutions and landscapes in The Woodlands.

- (a).Unkempt understory—homeowners disliked
- (b).Rustic open surface drainage channel—homeowners disliked
- (c).Manicured lawn and curb-and-gutter street—homeowners liked

Market studies also revealed that most homeowners prefer visually-appealing conventional drainage sewers. However, some of the ideas on water detention, for instance backyard detention, seemed to function on paper but did not work well in reality (Kutchin, 1998; Galatas and Barlow, 2004). Understory was also cleared in order to

increase commercial development visibility. The forest preserve helps to detain runoff especially in large storms. However, a large territory of the forest land was converted into residential and commercial uses after 1997 (Haunt, 2006). Some residents further undermined the ecological concepts by cutting backyard trees and clearing shrubs to expand their lawn areas (Forsyth, 2003; Galatas and Barlow, 2004).

Even though McHarg's ecohydrological planning approach was of vital importance to protect the community in the 1979 and 1994 storms, backyard detention was abandoned and open drainage was shifted to the conventional solutions (Galatas and Barlow, 2004). As a result, homeowners in The Woodlands started to complain about the flooded streets in large storms, similar to the complaints from conventionally developed communities in the Houston area (Haut, 2006).

4.8.2 Developer (Supplier)

From the developer side, the challenge lies in the conflict between long-term environmental stewardship and short-term economic gains. Crescent Real Estate Equities and Morgan Stanley Real Estate Fund II were the new owners during 1997-2003. They are conventional market-oriented developers and are largely profit-driven in their business ventures. The original plans were revised according to the homeowners' preferences and the market needs. Development sped up and short-term economic return was given the first priority.

As a result, McHarg's plans were by and large abandoned. Chapter II results show that soils with high permeability were not protected under the new ownership. Chapter III results show that McHarg's open surface drainage was changed to conventional curb-and-gutter drainage. Moreover, development occurred on the original forest preserve land. The original stringent ordinances of landscape preservation specified by McHarg's team were discarded.

4.8.3 Designer (Professional Service)

Barriers to implement the ecohydrological plans also came from the designers, as shown in two major debating issues: (1) the value system of professional service, and (2) the applicability of McHarg's planning approach. Conventionally-trained professionals believe that the market-driven type of professional service is the right kind of service they should provide. In addition, in the eyes of real estate and marketing professionals, McHarg's innovations were sometimes unrealistic and over demanding (Malone, 1985; Forsyth, 2005). For example, the landscape suitability map required to use environmental data as the key determinants of land-use location. Designers questioned the data accuracy (e.g., soil, vegetation) in preparing the environmental study, and the scale at which McHarg's planning approach is optimum.

For example, the survey data accuracy for site topography was not considered ideal by many members in the early planning team (Galatas and Barlow, 2004). McHarg suggested building around 50 small dams to detain runoff during heavy storms. But the

flat topography and the poorly-drained soils failed to offer effective drainage envisioned by McHarg. Robert Heineman believed that it was better to build a few large lakes or reservoirs where the topography and location were optimal. After that, a small number of strategically located detentions and retentions could be built (Kutchin, 1998; Galatas and Barlow, 2004). Changes were made as Heineman stated. Currently, there are two large lakes in The Woodlands, The Woodlands Lake (250 acres) and the Bear Branch Reservoir (70 acres), in addition to numerous small lakes and wetlands.

Data accuracy of the tree species was another concern. McHarg's plans specified a landscape clearance index in order to preserve trees of high ecological values. However, less variation of the tree species was found on site, similar to the less variation of soils. The ranking of ecological values presented another challenge to the design interpretation. The ranking will determine which tree to be preserved or cleared in the development, but the relatively arbitrary ranking led to constant dialogues regarding the various factors in determining the ranking. For example, designers were gauging on the values of pine trees versus hardwood trees, and mature trees versus young trees. If more mature trees are subject to dying, a hard choice needs to be made between mature trees and young trees (Malone, 1985; Kutchin, 1998; Galatas and Barlow, 2004).

Another challenge was the scale at which McHarg's planning approach could be applied. Heineman thought that McHarg's approach works best at the micro-level site design, rather than at the macro-level planning (Galatas and Barlow, 2004). Heineman agreed that McHarg's plan was helpful in allocating streets and shopping areas. But he suggested that an alternative procedure would be to determine the location of a particular land-use first. The next step would be to survey important environmental information

such as soil and vegetation. The final step is to respond to those environmental data in design. Some real estate professionals echoed this procedure and contended that land-use location would be determined by economic feasibility analysis rather than purely depending on environmental constraints (Galatas and Barlow, 2004; Forsyth, 2005).

4.8.4 Government (Policy Maker)

Government also presented some barriers to implement the ecohydrological plans. The question was to what extent government's support is available for private sector's innovations. In a typical American planning system, the public departments are too isolated to allow private sector's innovations to be successful (Forsyth, 2005). George Mitchell used his sophisticated political network and tremendous personal fortune to support The Woodlands project (Malone, 1985; Galatas and Barlow, 2004). Firstly, Mitchell strategically obtained almost absolute control of The Woodlands development for at least 25 years. In October 1971, Mitchell managed to place The Woodlands in the extraterritorial jurisdiction (ETJ) of Houston. At that time, Houston logically would not choose to annex The Woodlands soon because of the new town's indebtedness and low tax base. This allowed Mitchell to execute McHarg's plans without many hurdles (Morgan and King, 1987).

Secondly, Mitchell initiated The Woodlands project not purely for profit, but to experiment an American new town model in an attempt to find an a solution to the American urban problems (Malone, 1985; Kutchin, 1998). Mitchell's personal

commitment to the project, especially his financial support, was critical. In the 1960s, he used his own money to assemble 23,000 acres of land for the project. Additionally, it was Mitchell's energy company that invested \$28 million in infrastructure and improvement in The Woodlands as of 1974. Mitchell's energy company also provided substantial financial support to The Woodlands when it was on the verge of financial disasters in the 1970s international economic crisis and the 1980s Houston economic downturn.

Lastly, for a normal developer who was largely driven by short-term economic return, it would be a tremendous commitment to a mega project such as The Woodlands. The Woodlands project did not make profit until mid-1980s, some 10 years after its inception. The Woodlands economic specialist Jim McAlister recalled that Mitchell has put enormous personal investment into The Woodlands. Therefore, the development team, especially during the economic downturns, never believed that Mitchell will quit. Just as Mitchell, the team maintained a high level of passion and perseverance to accomplish the project (Kutchin, 1998; Galatas and Barlow, 2004). In contrast, most developers in the HUD bond gave up quickly when they did not see the light of profit. Among the 13 projects funded by the HUD, The Woodlands was the only project which has met its financial obligations, (Kutchin, 1998).

In the current planning system, if The Woodlands were initiated by another normal developer, it will never be as successful as it is today, at least in the environmental planning aspect (Galatas and Barlow, 2004). In summary, Mitchell's personal commitment and investment, the HUD \$50 million loan guarantee, and the

relatively flexible planning ordinances three decades ago were all important factors to make The Woodlands project.

4.9 Discussion

The main challenge of implementing McHarg's ecohydrological plans came from the long-term environmental benefits and the short-term economic gains. Homeowners' tastes largely influence developers' decision making process. Design professionals who believe in the market-driven type of professional service help encourage the conventional development.

In The Woodlands development, disagreement over McHarg's ecohydrological plan first rose from the professional side. Robert Heineman, Mitchell's in-house planner, was trained as a conventional land use planner. Heineman and many real estate professionals believed that the project economic viability was the most important consideration when they provided the professional service. Heineman also maintained that McHarg's approach was not applicable at the regional scale planning, but feasible at the site-level design. These statements, however, present limitations.

As one of HUD new town projects, The Woodlands was to address suburban sprawl, a regional problem, rather than a site-level design problem. The Woodlands meant to provide an alternative growth model in lieu of the urban sprawl model. In addition, McHarg's ecohydrological planning approach (i.e., landscape suitability analysis) was applicable across scales. At the regional scale, McHarg's approach

quantified the ecological values of critical natural resources, including hydrology, soils, vegetation, wildlife, and scenery. McHarg's approach also extended from the regional-scale planning to the site-scale design, such as in detention pond design and tree preservation design on individual lots.

Actually, many of the current stormwater management theories and practices could be found in McHarg's concepts 35 years ago. For example, EPA's Low Impact Development strategies suggest that the most effective way to treat stormwater runoff is to detain it as close to its source as possible (Coffman, 2000; USEPA, 2000). In The Woodlands development, McHarg already suggested similar principles as are used today.

Also, McHarg's ecohydrological planning approach is rather feasible today in the technical aspect. McHarg's team conducted an extensive soil and vegetation survey in the 1970s (WMRT, 1973a). Today, detailed environmental data (e.g., soil, vegetation, and topography) are available from various public agencies. McHarg's planning procedure and expected outcomes are also illustrated in the literature (McHarg, 1969; Steiner and Osterman, 1998; Ndubisi, 2002). Furthermore, with the aid of GIS, designers today could conduct a more polished analysis and synthesis.

McHarg's idea of design with nature and dwell in nature has set the premise for landscape architecture and planning professionals. However, it takes time for the general public to appreciate the ecohydrological planning approach. In fact, more accelerated changes are needed on the market side (homeowners and developers) towards a wider application of this planning approach. Developers by and large are conservative and hesitate to make major changes in the way they used to do business. This is because a single unpopular development may cause them huge financial loss. Bankers and others

who provide loans to developers tend to be even more conservative with regard to innovation and change. However, the long-term environmental benefits will diminish if the main emphasis is placed on the short-term economic return. Such has been the case when in the 1960s and 1970s, the environmental degradation became severe and a series of environmental acts came into play. Sadly, The Woodlands repeated this history. It got flooded twice in regional storms when its green infrastructure was sacrificed for development.

Lessons learned from these events shall educate developers, homeowners, as well as design professionals. The most effective approach in advocating the ecohydrological planning approach is to provide evidence that this approach will save in the long-term. For example, McHarg's open drainage design saved tremendous initial construction costs—\$14 million for Phase I alone. Besides these savings, the plans brought additional savings to the developer, since further benefits also increased when erosion, increased runoff, and flooding hazards were avoided, which were associated with conventional planning methods (McHarg, 1996).

Besides The Woodlands, open drainage system has been used at various scales. Almost all of them have demonstrated financial success. For example, Bellevue, Washington (pop. 100,000) planned an open drainage system in 1994. This system was integrated with its open space system. This stormwater management innovation saved expensive costs of engineered drainage system (Girling and Helphand, 1997).

Also started in the 1970s, another open drainage project but at a much smaller scale was Village Homes in Davis, California (Francis, 2002). In this 60-acre community project, the open drainage system saved nearly \$200,000 in development costs. Savings

from the conventional pipe drainage system were substantial enough to pay for most landscape improvement, including walkways, gardens, and other landscape amenities (Corbett and Corbett, 2000). In fact, several residential and commercial developments in Davis have mimicked Village Homes to adopt open drainage (Francis, 2002).

The natural open drainage system such as in The Woodlands and Bellevue provided multiple ecological and social benefits. Because protection of existing riparian corridors was an important component of the open drainage system, the system helped protect natural vegetation and habitat. Similar to The Woodlands, Bellevue survived storms in excess of one-hundred-year levels in 1984 and 1990 with little property damage (Girling and Helphand, 1994; 1997). The savings of construction costs and the potential savings of flooding damage serve excellent educational materials to homeowners and developers, towards a better understanding of McHarg's ecohydrological planning approach.

4.10 Conclusions

This study makes the ecohydrological planning information of The Woodlands available to practitioners and researchers. In addition, the study provides a critical review of the barriers to continue McHarg's planning approach. Lessons learned from The Woodlands development can help increase the collective knowledge about how to design with nature in a way which is environmentally benign and economically profitable.

It is obvious that the early success of The Woodlands' survival during regional significant storms has a close relationship with McHarg's ecohydrological plans. The Woodlands ceased to implement parts, if not all, of McHarg's plans especially after its ownership transition in 1997. Revisions of McHarg's plans have led to greater environmental impacts and made the community vulnerable to flooding.

McHarg's ecohydrological plans focused on stormwater management. The plans utilized a series of design strategies in order to maintain the natural hydrologic cycle after development. Key strategies included preserving permeable soils, preserving natural forest and using open drainage channels. The combination of different design strategies rather than relying on a single strategy increased the flood mitigation effectiveness. Conventional best management practices such as detention and retention ponds were also used to supplement those strategies.

Unfortunately, McHarg's approach was not followed after the first two villages. This approach was neither replicated at this scale elsewhere until today. The study reviews the barriers which prevented implementing McHarg's approach. Interestingly enough, McHarg used the economic savings to persuade Mitchell to adopt the open drainage proposal. It was because of the financial reason that McHarg's plans were abandoned by the dominant economic model. The slow market acceptance to innovations is universal. It takes time for the general public to appreciate the environmental and the economical benefits of McHarg's approach. After deviating from the original plans, flooding may cause more damage to The Woodlands in the future. The long-term benefits McHarg's plans could bring shall transcend the short-term economic gains.

This study advocates education as a way to foster ecohydrological planning. In this education agenda, design professionals shall play an important role. Educational materials describing successful cases, both economically and environmentally, will help increase homeowners' and developers' environmental consciousness. After all, it is the homeowners who take most care of their dwellings and value living in harmony with nature.

Replication of The Woodlands today may be a hard undertaking for a normal developer because of limited government support, stringent ordinances, and the level of commitment feasible under the dominant economic model. However, the comprehensive ecohydrological planning approach demonstrated in The Woodlands, stormwater management in particular, deserves further attention and wider application.

CHAPTER V

SUMMARY AND CONCLUSION

5.1 Review and Conclusions

This study examines McHarg's ecohydrological planning approach used in The Woodlands, Texas, after 35 years of its inception. The initial planning goals were to protect the forest environment after development and to maintain the site hydrologic balance. This study shows that a suite of strategies were proposed in a comprehensive way. Key strategies included (1) using soil permeability to coordinate land use location and density, (2) using open surface drainage, and (3) using a landscape clearance index to define the maximum vegetation clearance allowed on site. McHarg's planning approach was well implemented in the first two villages, and this study demonstrates that his approach has met the original planning goals. However, McHarg's planning approach was largely abandoned after The Woodlands ownership was changed in 1997.

Faithfulness to McHarg's approach protected the natural forests and led to effective flood mitigation. The Woodlands survived regional significant storms in 1979, 1987 and 1994 when neighborhoods nearby got severely flooded. Chapter II simulation study shows results similar to the study conducted by McHarg's team in the 1970s. If following McHarg's approach, The Woodlands would increase the watershed outflow by 55%, while the conventional Houston development would increase 180% (Spirm, 1985). This study also proves that using soil permeability to coordinate land-use density and

location is a viable solution to the flooding problem. Compared with land-use scenarios created with different planning approaches, McHarg's approach generates the least amount of stormwater runoff and is most likely to survive during intense storms.

Chapter III comparative study shows that McHarg's open drainage system is more effective than the conventional curb-and-gutter drainage system in detaining stormwater runoff. The early phases of development which used the open drainage system made little alteration to the site natural hydrologic cycle. Watershed after development resembled its pre-development forest conditions. In addition, the strategic location of different stormwater best management practices present important planning and design considerations.

Chapter IV archival study reveals that major planning strategies of McHarg's plans were largely abandoned after The Woodlands ownership was sold in 1997. Ecohydrological plans unfortunately stumbled and were adjusted to cater to the market needs—a conventional Houston suburban type of development. Deviation of McHarg's plans has led to adverse impacts on The Woodlands. Flooding was reported in 2000 and more recently in the 2008 Hurricane Ike. In Hurricane Ike, western Woodlands which took the conventional planning approach got severely flooded, whereas the early villages developed with McHarg's approach survived with little property damage (Madere, 2008).

Under the new ownership, the balance of short-term economic gains and long-term environmental stewardship was interrupted. The dominant economic model worships short-term investment return, while the long-term ecological benefits are less valued. Due to the nature of the market, developers are usually conservative and customer-oriented. In the eyes of homeowners, the rustic open drainage channels and the

unkempt understory look “messy”. Even to an educated eye, the ecological function that open drainage system provides may be less comprehensible. However, The Woodlands may be subjected to greater negative environmental impacts after its departure from the original planning concepts.

In retrospect, many contemporary sustainable development theories and practices (e.g., EPA’s Low Impact Development) could find their origins in McHarg’s concepts 35 years ago. It takes time for innovative planning strategies to be accepted and promulgated. It takes time to allow homeowners to enrich their environmental consciousness and adjust their dwelling preferences. It also takes time to increase the collective knowledge of the profession by revisiting exemplary cases such as The Woodlands.

McHarg’s idea of design with nature and dwell in nature has set the premise for landscape architecture and planning professionals. His rational method of creating healthy land use was systematically demonstrated in The Woodlands development. His Landscape Suitability Analysis (LSA) approach is rather feasible today in the technical sense. Detailed environmental data (e.g., soil, vegetation, and topography) are available from various public agencies. LSA procedure has been demonstrated in the literature (McHarg, 1969; Steiner and Osterman, 1998; Ndubisi, 2002). Furthermore, design professionals today could conduct a more polished analysis with the aid of GIS. It is the market side (homeowners and developers) that needs accelerated change towards a positive direction of sustainable development.

Innovative projects are vision-led. The Woodlands was. But it needs the right combination of good-intentioned developers and talented designers. George Mitchell

turned to McHarg because of his environmental planning expertise. But Mitchell's personal interests and commitment to the American new town model were also imperative. Mitchell launched this project not purely for profit. The Woodlands did not make profit ten years after its opening. It was Mitchell and his energy company that provided enormous financial support to the project. In this sense, replicating The Woodlands at this mega scale may be less likely today. Nonetheless, McHarg's ecohydrological planning approach deserves further application.

5.2 Study Limitation

A number of limitations present in this study. The first limitation is the limited time frame for a more comprehensive analysis. For example, the author did not conduct personal interviews to collect first-hand data in Chapter IV archival study. The author has made a number of visits to the site, conducting observations and has taken more than a hundred photographs. Due to the limited time frame, no interviews were conducted.

The second limitation lies in data availability and quality. In Chapter III comparative study, flow data from the USGS is missing from 1977 to 1998. Also, the attribute table information of GIS parcel data after 2003 was not available. The data availability made it impossible to conduct a study of 35-year time span. Likewise, Chapter II simulation study may present some artifacts because of data quality. The land use and land cover data sets obtained from various national datasets are prepared at

different scales. In addition, these datasets show inconsistencies, making it difficult to judge the land use and land cover change overtime.

The third limitation comes from the research design. In Chapter III comparative study, the flood routing issue was not take into account. In addition, several confounding variables caused challenges to directly evaluate the different drainage solutions. These variables included soil composition, vegetation cover percentage, developed area, etc. McHarg used grassed swales because more permeable soils are available to provide infiltration opportunities. However, the recharge effectiveness will decrease because less permeable soils are in the later phases.

Furthermore, Chapter II simulation study did not take into account vegetation and topography key environmental factors which McHarg used in preparing the environmental plan. Chapter II simulation study meant to replicate McHarg's procedure of allocating different land uses onto different soil groups. McHarg's plans have revised the site topography for an alternative drainage pattern. However, this step was not conducted due to the sophisticated procedures in the hydrologic models.

5.3 Future Research

This study is only a starting point of a longer research agenda on The Woodlands. Further research is needed on several fronts. Firstly, future study shall look into residents' recognitions of McHarg's ecohydrological planning approach overtime. The Woodland did not experience any flooding in the early phases. However, it got flooded

twice when McHarg's approach was largely abandoned. In this regard, homeowners who stick to conventional development may form a different opinion on McHarg's planning innovations.

A similar question is raised for the design professionals. The Woodlands planning and design team presents a dichotomy. One side maintains that McHarg's approach should be followed, while the other side insists on the market-driven, conventional type of development. Currently, the latter side is gaining upper hand since Robert Heineman, vice president for planning, and Roger Galatas, former president of The Woodlands Corporation, both think what The Woodlands needs is the a conventional Houston type of development. However, after the flooding events in The Woodlands, the conventional side professionals may realize the need to adjust their professional value systems.

Secondly, the next step shall investigate the water quality issue in The Woodlands development. This study only examines the water quantity issue, flooding in particular. The water quality component shall be added to examine the impacts of different planning approaches on stormwater quality. Some other aspects within this context could also be examined. For instance, the function of riparian vegetation on water quality could be investigated.

Finally, future study needs to probe deeper into the policy implications for community planning and design. The next step shall investigate the effectiveness of planning guidelines and regulations that create the development impacts. Further study shall unveil the policy barriers to implement sustainable planning and design practices.

REFERENCES

- Alberti, M., Booth, D., Hill, K., Coburn, B., Avolio, C., Coe, S., Spirandelli, D., 2007. The impact of urban patterns on aquatic ecosystems: an empirical analysis in Puget lowland sub-basins. *Landscape and Urban Planning* 80(4), 345-361.
- Alberti, M., Marzluff, J. M., 2004. Ecological resilience in urban ecosystems: linking urban patterns to human and ecological functions. *Urban Ecosystems* 7(3), 241-265.
- Allen, P.M., J.G. Arnold, Skipworth, W., 2002. Erodibility of urban bedrock and alluvial channels, North Texas. *Journal of American Water Resources Association* 38(5), 1477-1492.
- Arnold, C. L., Gibbons, C. J., 1996. Impervious surface coverage - the emergence of a key environmental indicator. *Journal of the American Planning Association* 62(2), 243-258.
- Arnold, J. G., Allen, P. M., 1999. Automated methods for estimating baseflow and ground water recharge from streamflow records. *Journal of the American Water Resources Association* 35(2), 411-424.
- Arnold, J.G., Fohrer, N., 2005. SWAT2000: current capabilities and research opportunities in applied watershed modeling. *Hydrological Processes* 19(3), 563-572.
- Arnold, J. G., Williams, J. R., Srinivasan, R., King, K. W., Griggs, R. H., 1994. SWAT: soil water assessment tool. U. S. Department of Agriculture, Agricultural Research Service, Grassland, Soil and Water Research Laboratory, Temple, TX.
- Bedient, P., Flores, A., Johnson, S., Pappas, P., 1985. Floodplain storage and land-use analysis at the Woodlands, Texas. *Water Resources Bulletin* 21(4), 543-551.
- Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Donigian, A.S., Johanson, R.C., 1996. Hydrologic simulation program-FORTRAN user's manual, version 11. USEPA, Athens, GA.
- Booth, D. B., Jackson, C. R., 1997. Urbanization of aquatic systems: Degradation thresholds, stormwater detection, and the limits of mitigation. *Journal of the American Water Resources Association* 33(5), 1077-1090.
- Burchell, R.W., Lowenstein, G., Dolphin, W.R., Galley, C.C., Downs, A., Seskin, S., Still, K.G., Moore, T., 2002. *Costs of sprawl—2000*. National Academy Press, Washington, DC.

Clay, G., 1998. The national observer: The Woodlands. *Landscape Architecture* 88(9), 131-132.

Coffman, L., 2000. *Low-Impact Development Design Strategies, an Integrated Design Approach*. EPA 841-B-00-003. Department of Environmental Resources, Programs and Planning Division, Prince George's County, Maryland.

Corbett, C. W., Wahl, M., Porter, D. E., Edwards, D., Moise, C., 1997. Nonpoint source runoff modeling - a comparison of a forested watershed and an urban watershed on the South Carolina coast. *Journal of Experimental Marine Biology and Ecology* 213(1), 133-149.

Echols, S., 2008. Split-flow theory: stormwater design to emulate natural landscapes. *Landscape and Urban Planning* 85(3-4), 205-214.

Ellis, J. B., Marsalek, J., 1996. Overview of urban drainage: environmental impacts and concerns, means of mitigation and implementation policies. *Journal of Hydraulic Research* 34(6), 723-731.

Ewing, R., 1997. Is Los Angeles-style sprawl desirable? *Journal of American Planning Association* 63 (1), 107-126.

Ferguson, B. K., 1991. The failure of detention and the future of stormwater design. *Landscape Architecture* 81(12), 76-79.

Ferguson, B. K., 1995. Storm-water infiltration for peak-flow control. *Journal of Irrigation and Drainage Engineering* 121(6), 463-466.

Ferguson, B. K., 1998. *Introduction to Stormwater*. John Wiley and Sons, New York.

Ferguson, B. K., Suckling, P. W., 1990. Changing rainfall-runoff relationships in the urbanizing Peachtree Creek watershed, Atlanta, Georgia. *Water Resources Bulletin* 26(2), 313-322.

Forsyth, A., 2002. Planning lessons from three US new towns of the 1960s and 1970s - Irvine, Columbia, and The Woodlands. *Journal of the American Planning Association* 68(4), 387-415.

Forsyth, A., 2003. Ian McHarg's Woodlands: a second look. *Planning*, August, 10-13.

Forsyth, A., 2005. *Reforming Suburbia: The Planned Communities of Irvine, Columbia, and The Woodlands*. University of California Press, CA.

Francis, M., 2001. A case study method for landscape architecture. *Landscape Journal* 20, 15-29.

Francis, M., 2002. Village homes: a case study in community design. *Landscape Journal* 21, 23-41.

Galatas, R., Barlow, J., 2004. *The Woodlands: the inside story of creating a better hometown*. Urban Land Institute, Washington DC.

Gause, J. A., Garvin, A., Kellenberg, S. R., 2002. *Great planned communities*. Urban Land Institute, Washington DC.

Girling, C., Helphand, K. I., 1994. *Yard, Street, Park: The Design of Suburban Open Space*. John Wiley and Sons, New York.

Girling, C., Helphand, K., 1997. Retrofitting suburbia: open space in Bellevue, Washington, USA. *Landscape and Urban Planning* 36, 301-313.

Girling, C., Kellett, R., 2005. *Skinny Streets and Green Neighborhoods: Design for Environment and Community*. Island Press, Washington, DC.

Corbett, J., Corbett, M., 2000. *Designing Sustainable Communities: Learning from Village Homes*. Island Press, Washington, DC.

Hammer, T. R., 1972. Stream channel enlargement due to urbanization. *Water Resources Research* 8(6), 1530-1540.

Hann, C.T., Barfield, B.J., Hayes, J.C., 1994. *Design Hydrology and Sedimentology for Small Catchments*. Academic Press, San Diego.

Hannah, D.M., Wood, P.J., Sadler, J.P., 2004. Ecohydrology and hydroecology: a 'new paradigm'? *Hydrological Processes* 18, 3439-3445.

Haut, R., 2006. Environmental action plan: The Woodlands, Texas, <http://files.harc.edu/Documents/Announcements/2007/WoodlandsEnvironmentalActionPlan.pdf>.

Hernandez, M., Semmens, D. J., Miller, S. N., Goodrich, D. C., Kepner, W. G., 2005. Development and application of the automated geospatial watershed assessment tool, in: modeling and remote sensing applied to agriculture (U.S. and Mexico) (C. W. Richardson, A. D. Baez-Gonzalez, Tiscareno-Lopez, eds.). USDA-INIFAP Publication, Aguascalientes, Mexico, 127-158.

Horner, R., Lim, H., Burges, S. J., 2002. Hydrologic monitoring of the Seattle ultra-urban stormwater management projects, in: *Water Resources Series Technical Report (No. 170)*. University of Washington, Seattle.

Huber, W.C., et al., 1981. Storm Water Management Model Users Manual, Version III, EPA-600/2-84-109A. Environmental Protection Agency, Cincinnati, OH.

Jennings, D.B., Jarnagin, S.T., 2002. Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-Atlantic subwatershed. *Landscape Ecology* 17, 471-489.

Kim, J. K., 2005. Exploring the effects of local development regulations on ecological landscape structure. Ph.D. Dissertation. Texas A&M University, College Station, TX.

Kundzewicz, Z.W., 2002. Ecohydrology—seeking consensus on interpretation of the notion. *Hydrological Sciences* 47(5), 799-804.

Kutchin, J., 1998. How Mitchell Energy & Development Corp. Got Its Start and How It Grew. Mitchell Energy & Development Corporation, The Woodlands, Texas.

Lance, M., 1982. Building a city from scratch, in: *Southwest Airlines Magazine*, August.

Lemons, P.J. McCray, J.E., 2007. Modeling hydrology in a small Rocky Mountain watershed serving large urban populations. *Journal of American Water Resources Association* 43(4), 875-887.

Leopold, L.B., 1968. Hydrology for urban land planning: a guidebook on the hydrologic effects of urban land use. U.S. Geological Survey Circular 554.

Madere, M., 2008. Tropical weather: The Woodlands archives (Houston Chronicle), http://blogs.chron.com/hurricanes/the_woodlands/.

Malone, M., 1985. *The Woodlands: New Town in the Forest*. Pioneer Publications, Inc, Houston.

Marsh, W. M., 1997. *Landscape Planning: Environmental Applications*. John Wiley & Sons, New York.

McHarg, I. L., 1969. *Design with Nature*. Doubleday/Natural History Press, New York.

McHarg, I. L., 1996. *A Quest for Life: An Autobiography*. John Wiley and Sons, New York.

McHarg, I. L., Steiner, F.R., 1998. *To Heal the Earth: Selected Writings of Ian L. McHarg*. Island Press, Washington DC.

McHarg, I. L., Sutton, J., 1975. Ecological plumbing for the Texas coastal plain: The Woodlands New Town Experiment. *Landscape Architecture* 65(1), 80-90.

Miller, S. N., Semmens, D. J., Goodrich, D. C., Hernandez, M., Miller, R. C., Kepner, W. G., Guertin, D. P., 2007. The automated geospatial watershed assessment tool. *Environmental Modeling & Software* 22(3), 365-377.

Morgan, G., King, J., 1987. *The Woodlands: New Community Development 1964-1983*. Texas A&M University Press, TX.

Nash, J., Sutcliffe, J., 1970. River flow forecasting through conceptual models part I—A discussion of principles. *Journal of Hydrology* 10(3), 282-290.

National Climatic Data Center (NCDC), 2008. Available from: <http://www.ncdc.noaa.gov/oa/ncdc.html>

National Hydrograph Dataset (NHD), 2008. Available from: <http://nhd.usgs.gov>

National Oceanic and Atmospheric Administration (NOAA), 2000. National Weather Service Storm Data and Unusual Weather Phenomena. Available from: www.srh.noaa.gov/hgx/severe/2000/apr00hgx.pdf

National Oceanic and Atmospheric Administration (NOAA), National Weather Service Forecast Office, 1987. Some Recent September Severe Weather Highlights for Southeast Texas. Available at <http://www.srh.noaa.gov/hgx/severe/events/september.htm>

National Oceanic and Atmospheric Administration (NOAA), 2008. NOAA Coastal Change Analysis Program. Available from: <http://www.noaa.gov/>

Natural Resources Conservation Service. Soil Survey Geographic (SSURGO) Database. Available from: <http://soils.usda.gov/survey/geography/ssurgo/>

Nassauer, J., 1995. Messy ecosystems, orderly frames. *Landscape Journal* 14 (2), 161-170.

Neuman, M., 2000. Regional design: recovering a great landscape architecture and urban planning tradition. *Landscape and Urban Planning* 47(3-4), 115-128.

Ndubisi, F., 2002. *Ecological Planning: A Historical and Comparative Synthesis*. The Johns Hopkins University Press, Baltimore, Maryland.

Paul, M. J., Meyer, J. L., 2001. Streams in the urban landscape, *Annual Review of Ecology and Systematics* 32, 333-365.

Perez-Pedini, C., Limbrunner, J. F., Vogel, R. M., 2005. Optimal location of infiltration-based best management practices for storm water management. *Journal of Water Resources Planning and Management* 131(6), 441-448.

Prince George's County, Department of Environmental Resources. 1999. Low-Impact Development Design Strategies: An Integrated Design Approach. Department of Environmental Resources, Programs and Planning Division.

Rogers, G.O., DeFee, B.B., 2005. Long-term impact of development on a watershed: early indicators of future problems. *Landscape and Urban Planning* 73, 215-233.

Schueler, T.R., 1994. The importance of imperviousness. *Watershed Protection Techniques* 1, 100-111.

Shadish, W.R., Cook, T.D., Campbell, D.T., 2002. *Experimental and Quasi-Experimental Designs for Generalized Causal Inference*. Houghton Mifflin, Boston.

Smith, R. E., Goodrich, D. C., Woolhiser, D. A., Unkrich, C. L., 1995. KINEROS-- A kinematic runoff and erosion model, in: *Computer Models of Watershed Hydrology* (V. P. Singh, ed.). Water Resources Publications, Highlands Ranch, CO, 697-732.

Soil Conservation Service, 1972. *Soil survey of Montgomery County, Texas*. U.S. Government Printing Office, Washington, DC.

Soil Conservation Service, 1986. *Urban hydrology for small watersheds*, Technical release No.55. Soil Conservation Service, U.S. Department of Agriculture, Washington, DC.

Spirn, A. W., 1984. *The Granite Garden: Urban Nature and Human Design*. Basic Books, New York.

Srinivasan, R., Arnold, J. G., 1994. Integration of a basin-scale water-quality model with GIS. *Water Resources Bulletin* 30(3), 453-462.

Srinivasan, R., Ramanarayanan, T. S., Arnold, J. G., Bednarz, S. T., 1998. Large area hydrologic modeling and assessment - Part II: Model application. *Journal of the American Water Resources Association* 34(1), 91-101.

Stake, R.E., 1995. *The Art of Case Study Research*. Sage Publication, Thousand Oaks, CA.

Steiner, F.R., Osterman, D.A., 1998. Landscape planning: a working method applied to a case study of soil conservation. *Landscape Ecology* 1 (4), 213-226.

Stone, B., 2004. Paving over paradise: how land use regulations promote residential imperviousness, *Landscape and Urban Planning* 69(1), 101-113.

Texas Natural Resources Information System (TNRIS), 2008. Available from: <http://www.tnris.state.tx.us/>

The Woodlands Development Company, 2007. The Woodlands, Texas Demographics, January 1, 2007. The Woodlands Development Company.

Tunney, K. W., 2001. Innovative stormwater design: the role of the landscape architect. *Stormwater: The Journal for Surface Water Quality Professionals* 2(1), 30-43.

U.S. Army Corps of Engineers, 1982. A permit to place fill material associated with the construction of two water retention structures and perform channel modifications in Spring Creek, in Bear Branch and Panther Branch tributaries at locations in Montgomery County, Texas. Permit number: 15336.

U.S. Army Corps of Engineers, 1985. HEC-1 Flood Hydrology Package Users Manual. Hydrologic Engineering Center, Davis, CA.

U.S. Department of Agriculture (USDA), 1986. Urban Hydrology for Small Watersheds. Natural Resources Conservation Service. Conservation Engineering Division, Technical Release 55.

U.S. Department of Agriculture (USDA), 2002. Natural Resources Conservation Service (NRCS), National Soil Survey Handbook, Title 430-VI.

U.S. Environmental Protection Agency (USEPA), 2000. Low Impact Development (LID) A Literature Review EPA-841-B-00-005.

U.S. Environmental Protection Agency (USEPA), 2001. Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) v.3.0 User's Manual, EPA-823-B01-001. Office of Water, USEPA, Washington, DC.

U.S. Geological Survey (USGS), 2005. National hydrograph dataset (NHD). Available from: <http://nhd.usgs.gov/>

U.S. Geological Survey (USGS). National land cover dataset 2001 (NLCD). Available from: <http://seamless.usgs.gov/website/seamless/products/nlcd01.asp>

U.S. Geological Survey (USGS), 2008. Available from: <http://www.usgs.gov>

Van Liew, M. W., Garbrecht, J., 2003. Hydrologic simulation of the Little Washita River experimental watershed using SWAT. *Journal of the American Water Resources Association* 39 (2), 413-426.

WMRT (Wallace, McHarg, Roberts, and Todd), 1971. Ecological Planning Study for the New Community. Wallace, McHarg, Roberts and Todd: Philadelphia.

WMRT (Wallace, McHarg, Roberts, and Todd), 1973a. Woodlands New Community: An Ecological Inventory. Wallace, McHarg, Roberts and Todd: Philadelphia.

WMRT (Wallace, McHarg, Roberts, and Todd), 1973b. Woodlands new community: Guidelines for site planning. Philadelphia: Wallace, McHarg, Roberts and Todd.

WMRT (Wallace, McHarg, Roberts, and Todd), 1973c. Woodlands New Community: Phase One: Land Planning and Design Principles. Philadelphia: Wallace, McHarg, Roberts and Todd.

WMRT (Wallace, McHarg, Roberts, and Todd), 1974. Woodlands New Community: An Ecological Plan. Philadelphia: Wallace, McHarg, Roberts and Todd.

Yin, R.K., 1993. Applications of Case Study Research. Sage Publication, Thousand Oaks, CA.

Yin, R.K., 1994. Case Study Research: Design and Methods. Sage Publication, London.

VITA

Name: Bo Yang

Address: Department of Landscape Architecture & Urban Planning, Texas
A&M University, 3137 TAMU, College Station, Texas 77843-3137

Email Address: martin_tamu@yahoo.com

Education: B.Arch., Architecture, Huazhong University of Science &
Technology, 2002

M.Arch., Architecture, Huazhong University of Science &
Technology, 2005

Ph.D., Landscape Architecture & Urban Planning, Texas A&M
University, 2009